R-2345-AF

The Use of Prototypes in Weapon System Development

G. K. Smith, A. A. Barbour, T. L. McNaugher,
M. D. Rich, W. L. Stanley

March 1981

Rand
PROJECT AIR FORCE

The research reported here was sponsored by the Directorate of Operational Requirements, Deputy Chief of Staff/Research, Development, and Acquisition, Hq USAF, under Contract F49620-82-C-0018. The United States Government is authorized to reproduce and distribute reprints for governmental purposes notwithstanding any copyright notation hereon.

Library of Congress Cataloging in Publication Data
Main entry under title:

The use of prototypes in weapon system
development.

"R-2345-AF."
1. United States. Air Force--Procurement.
2. United States. Air Force--Weapons systems.
I. Smith, Giles K., 1928- . II. United
States. Air Force. III. Rand Corporation.
UG1123.U83 358.4'16212'0973 82-5416
ISBN 0-8330-0400-X AACR2

The Rand Publications Series: The Report is the principal publication documenting and transmitting Rand's major research findings and final research results. The Rand Note reports other outputs of sponsored research for general distribution. Publications of The Rand Corporation do not necessarily reflect the opinions or policies of the sponsors of Rand research.

Published by The Rand Corporation

R-2345-AF

The Use of Prototypes in Weapon System Development

G. K. Smith, A. A. Barbour, T. L. McNaugher,
M. D. Rich, W. L. Stanley

March 1981

A Project AIR FORCE report
prepared for the
United States Air Force

Rand
SANTA MONICA, CA 90406

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	R-2345-AF
2. GOVT ACCESSION NO.	[illegible]
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle)	The Use of Prototypes in Weapon System Development
5. TYPE OF REPORT & PERIOD COVERED	Interim
6. PERFORMING ORG. REPORT NUMBER	
7. AUTHOR(s)	G. K. Smith, A. A. Barbour, T. L. McNaugher, M. D. Rich, W. L. Stanley
8. CONTRACT OR GRANT NUMBER(s)	F49620-81-C-0018
9. PERFORMING ORGANIZATION NAME AND ADDRESS	The Rand Corporation 1700 Main Street Santa Monica, CA 90406
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS	
11. CONTROLLING OFFICE NAME AND ADDRESS	Requirements, Programs and Studies Group (AF/RDQM) Ofc, DCS/R&D and Acquisition Hq USAF, Washington, D.C. 20330
12. REPORT DATE	March 1981
13. NUMBER OF PAGES	181
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	
15. SECURITY CLASS. (of this report)	Unclassified
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

no restrictions

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Acquisition
Armed Forces Procurement
Prototypes
Military Aircraft

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

see reverse side

UNCL

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

This study examines the role of prototypes in the contemporary environment of weapon system acquisition. The research draws on case studies of four systems (two Air Force airplanes and two Army helicopters) that were developed in the early 1970s and that used prototypes in various ways. These were compared with a broad range of acquisition programs that used other acquisition strategies. The objective of the study is to sharpen the understanding of advantages and disadvantages of prototyping and conditions under which its use may be advantageous. Section II presents an outline of the different kinds of prototypes, and the various objectives that might be sought in a prototype phase. The section concludes with a description of the analysis procedure, a summary of the four systems examined, and the source of data on nonprototype programs used for comparison. Section III summarizes the results of the research, and Section IV contains the conclusions. Four appendixes are attached, each describing one of the case studies.
*****

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

PREFACE

During the 1950s and 1960s Rand conducted a number of studies on the use of prototypes in weapon system development. Those analyses were based on case studies of systems developed during the late 1940s and the 1950s, when prototyping was a common practice. As acquisition strategies evolved during the succeeding years, the continuing validity of the earlier results became questionable, but there was little modern evidence to draw upon until the early 1970s, when several new development programs included a prototype phase.

This study examines the role of prototypes in the contemporary environment of weapon system acquisition. The research draws on case studies of four systems (two Air Force airplanes and two Army helicopters) that were developed in the early 1970s and that used prototypes in varying ways. The research objective is to sharpen the understanding of the various advantages and disadvantages of prototyping and the conditions under which its use may be advantageous.

This study was performed as part of Rand's continuing research in weapon system acquisition strategy and policy; it was conducted under the "Air Force Acquisition Options for the 1980s" project of the Project AIR FORCE Resource Management Program. Results should be of interest to Service and DoD personnel involved in the design of weapon system acquisition policy and in the management of specific acquisition programs.

SUMMARY

The development of any new weapon system involves numerous risks and uncertainties. How those risks and uncertainties are accommodated constitutes a major element of the acquisition strategy. One method is at some point in the development cycle to build one or more "prototypes" to resolve certain issues through full scale test and demonstration.

This research was undertaken to sharpen our understanding of the various advantages and disadvantages of prototyping and of the conditions under which it might profitably be applied in today's environment. We restricted our research to prototypes that are preliminary versions of a possible future weapon system, assembled and tested to resolve some issues or reduce certain risks before the Service makes a commitment to additional phases of the acquisition. In some cases there may be no commitment to complete development and procurement of the system, and the prototype would then be developed as a hedge against the possibility that a system of that type may be needed in the near future. We therefore exclude "experimental" prototypes designed to learn about some technical design concept and "pre-production" prototypes, found in almost every development program, used to validate the detail characteristics of the fully developed system before the initiation of high-rate production.

We examined four weapon system acquisition programs of the 1970s that had a prototype stage and compared them with a broad range of acquisition programs that used other acquisition strategies. The four programs selected for analysis were:

1. AX (YA-9 and YA-10)
2. Lightweight Fighter (YF-16 and YF-17)
3. Advanced Attack Helicopter (YAH-63 and YAH-64)
4. Utility Transport Helicopter (UH-60 and UH-61)

By comparing the outcomes of these programs with those of contemporary systems that had not utilized a prototype phase, we sought answers to two broad questions:

- Did the outcomes of the programs having a prototype stage differ in any significant and consistent way with other programs that had omitted a prototype phase? If so, what were the characteristics and attributes of the prototype phase that contributed most to the beneficial outcomes?
- From those programs, what specific lessons can be derived that can be applied to the acquisition of similar systems in the future? If a prototype phase seems appropriate, how should that phase be designed and managed to provide the greatest benefits to the overall program?

Prototypes offer an opportunity for achieving several different kinds of benefits, and the actual mix of benefits may vary from one program to another, depending on the needs and circumstances of each program. In this study we examined three classes of possible benefits:

1. *Efficiency During Development.* Development of a new weapon system involves a large number of technical difficulties, and inevitably some things will go wrong. One approach for coping with this problem is to introduce a prototype phase early in the program, usually before proceeding to full scale development. Even though the prototype may not be exactly like the final system, many potential problems will

probably be revealed. Corrective actions can be taken before the final system design, and frequently those corrective actions can be proof-tested on the prototype. Two kinds of benefits should emerge from this process: (1) the acquisition will cost less, because fewer corrective actions will be needed after completion of full scale development and (usually) some production, where changes can be very expensive; and (2) the quality of the final product should be somewhat enhanced, because some of the flaws will have been eliminated. The use of competition during the prototype phase is examined as one means of achieving additional efficiencies.

2. *Improving the Quality of Decisions.* The efficiency arguments discussed above were directed at a set of micro decisions, each dealing with a specific design problem. A typical development program involves many such decisions. There are also a few macro decisions, usually occurring at major program milestones and dealing with whether the program should proceed to the next phase. Prototype test results should be useful in providing added confidence at the decision to proceed into full scale development. Similarly, those same test results would be valuable in making a selection between competitive sources at that point in the acquisition cycle.
3. *Hedging Against Uncertainties.* A prototype usually costs a small fraction of a full system development, and thus may sometimes be started as a hedge against a future operational need, but without waiting until the need is sufficiently certain to justify full system development. Or, if exceptionally high technical risks are involved, two or more different approaches to the design might be carried through the prototype phase to hedge against the possible failure of one approach.

PROTOTYPE COSTS AND BENEFITS

The four programs examined in this study provided examples of each kind of objective. Unfortunately, the small sample size precluded a definitive comparison with other programs that had not used a prototype phase, but we can infer some cost/benefit comparisons from the limited evidence.

An austere prototype phase of a large program can cost as little as 1 percent of the total acquisition cost, even if dual competitive sources are used. If, as in the UTTAS program, the issue to be resolved requires that nearly the complete system be prototyped and tested, and the expected procurement quantities are modest, costs can approach 10 percent of total acquisition per source. The actual net cost of the prototype phase is probably somewhat less than the apparent direct cost because of subsequent savings in the FSD, production, and operations phases. There is some evidence that on average, cost growth of prototyped programs is less than that of conventional acquisition programs, and the magnitude of such savings is much greater than the direct cost of the prototype phase. However, such "savings" may simply be a reflection of more accurate (higher) initial estimates of cost and therefore should not be equated to any reduction in real cost.

The time required to develop a new system is another important resource that must be considered in selecting a development strategy. It has long been asserted that inserting a prototype phase lengthens the total acquisition time. However, the histories of attack and fighter aircraft developed by the Navy and the Air Force since 1950 indicate that introducing a prototype makes little difference in the total development time. Furthermore, if a prototype program can be started earlier than could an equivalent full scale development program (as was certainly the case with the LWF program), then use of a prototype phase may actually lead to an *earlier* fielding date.

Of course, any comparison of fielding date (IOC, first operational delivery, etc.) is complicated by the fact that truly effective operational capability is sometimes delayed several years because of problems in system performance and reliability. If, as seems likely, a prototype phase can lead to a system with fewer such problems when production starts (see below), that effect could add another important saving in total effective acquisition time. Unfortunately, we have no practical way to measure the "effective" operational date, so this potential benefit of prototyping cannot be quantitatively analyzed.

Did the outcomes of the prototyped programs differ from those of conventional programs enough to justify the dollar costs? Below we review each class of potential benefits.

In each of the four programs, the prototype phase contributed to the process of identifying and correcting design flaws, but the efficiency (and thus the benefit) of that process varied substantially. In the two Air Force projects, the prototype phase provided an opportunity to identify and correct numerous design deficiencies more quickly and cheaply than would have been the case in a conventional full scale development program. Design problems were also identified and corrected in the prototype phase of the helicopter programs, but there the engineering work conducted on the prototypes was nearly equivalent to that of a normal full scale development, so there was less opportunity for achieving an appreciable gain in efficiency.

All four of the systems reviewed in this study used two competitive sources throughout the prototype phase. In the two Air Force programs, the system program manager had a very small staff during the prototype phase, relying instead on the competitive environment to ensure that the contractors performed effectively. The Air Force managers uniformly believed that the arrangement was highly successful. Conversely, the Army prototype programs had detailed contracts and extensive Program Office staffs, reducing the opportunities for exploiting the competitive environment as a substitute for Project Office management controls over the contractors.

Nearly everyone agreed that the contractors were more responsive to Program Office direction while in a competitive environment than they were after entering into the sole-source phase of the program. Although this effect cannot be measured in any practical way, it is an important potential benefit. Many experienced managers believe that the efficiencies resulting from a competitive environment during a part of the development phase could exceed the direct costs involved.

There is little evidence that the quality of cost and performance data available at the end of the prototype phase led to program decisions or predictions substantially better than those of typical programs lacking a prototype phase. Each prototyped program has experienced some cost growth since the start of full scale development, and none of the four programs involved exceptional technical risks.

Prototype test results undoubtedly contributed to source selection for the subsequent development and production phases, and anecdotal evidence indicates that in at least some cases the test results led to selection of a source different from the one that would have been selected on the basis of "paper" design proposals. However, in these cases the second best would probably have been nearly as good, so the value of this benefit is difficult to assess.

The LWF program was designed mostly as a hedge against the possible need for a system quite different from the ones then being developed and procured for the tactical air forces. By the time the prototypes had entered flight test, it was decided that such a system was needed, and the program quickly moved into full scale development. The prototype phase was a tangible option, a catalyst for the full system-level decision, and it permitted an earlier operational capability.

In the LWF program we can confidently identify some ways a prototype phase affected the program outcomes, but in the other three programs the prototype phase effects were smaller or subject to considerable uncertainty. In the AX, AAH, and UTTAS programs the prototypes did not affect any major program decision except source selection, and in those three cases source selection does not seem to have been a pivotal issue. There is some evidence that all four programs benefited from competition and that two of the programs achieved some development efficiency through early, low cost detection of design flaws, but those effects are impossible to measure in any confident way. Our inability to measure such benefits should not be interpreted as indicating their lack of importance; the sample size is too small to permit more confident conclusions.

PROGRAM ORGANIZATION AND MANAGEMENT

There is no widely accepted doctrine on how to organize or manage a prototype program, nor is there even a well developed body of literature on the subject. The prototype programs reviewed in this study involved a wide variety of management organization and style. Nevertheless, we believe even this varied set of experiences supports three lessons.

If development efficiency is a major objective of the program, a flexible contracting and management structure seems necessary. If a sizable number of design flaws are detected early and at low cost, and if the designers then have the freedom and incentive to devise and test solutions to those problems quickly, some efficiencies will have been achieved. The two Air Force programs studied here achieved those goals by using competition to provide incentives and by not contractually obligating the industry teams to achieve any specified set of performance capabilities or to follow any particular design practices or procedures. That kind of flexible contracting and management is very different from the usual structure applied to most weapon system development programs during the past couple of decades.

System Program Office personnel believe that the competition stimulated the industry teams to work at higher levels of dedication and efficiency than would otherwise have been the case. However, the desirability of a second competitive source in the prototype phase depends on the characteristics and objectives of a particular program and must be assessed individually in each case.

Finally, to obtain maximum benefit from the prototype, the full system operations concept should be well thought out before the prototype phase is begun. Many decisions made during the design process, even at the prototype level, depend on how the eventual weapon system is expected to be operated. Possibly more important, it is not otherwise possible to assess the objectives of the prototype phase accurately or to ensure that the prototype includes the correct system elements. Every effort should be taken to ensure that the design concept developed in the prototype phase will be the one taken into full scale development. Any changes in design concept or performance specification introduced after the prototype phase (except those dictated by prototype test results) will diminish the benefits of that phase.

WHEN SHOULD PROTOTYPES BE USED?

If the new system involves much technical risk, and almost every new weapon system will involve such risks, a prototype phase can probably improve the efficiency of finding and

correcting many of the inevitable design flaws. A prototype program that includes the initial development and test of the most critical system components, together with a contractual and management strategy that permits rapid and flexible response to technical problems, can resolve many of those problems with a fairly small investment of time or money. If those same flaws emerge only at the end of full scale development, where major investments have already been made in production facilities and all the complex infrastructure needed to produce and operate a new system, their correction is much more difficult and expensive.

Another use of prototypes that appears promising in today's environment is to use an austere prototype as a way of hedging against uncertainty in future operational needs. A prototype of one or more such candidate solutions, started early in the decision process, may create or preserve an important option. If, sometime later, one of the prototyped designs is deemed responsive to an operational need and the decision is made to complete the development, then the experience gained in the prototype phase can lead to a faster and lower-cost development completion, and the decisionmaker can have somewhat higher confidence in the predicted program outcomes.

The conditions under which these benefits may be considered sufficient to justify the associated cost of a prototype phase is highly situation dependent, but enough experience exists that managers should be able to appraise their own program and decide if a prototype phase would be appropriate.

RECOMMENDATIONS

Prototyping should be treated as one of several standard and acceptable development options. During the concept formulation of every new weapon system, the project manager should review the possible benefits of using a prototype phase. Acquisition policies and procedures should encourage a prototype phase early in the evolution of a new weapon system, so that critical hardware development could proceed at modest cost while the need for a full system development and production program was still being debated.

Management of a prototype phase is frequently very different from management of a full scale development program. Prototype management experience should be systematically accumulated so that each manager faced with organizing and conducting a prototype program could draw on the experience of previous programs.

ACKNOWLEDGMENTS

This research could not have been conducted without the extensive assistance generously provided by personnel in the Program Offices of the four weapon systems studied herein, and by the personnel in the firms that served as prime contractors during the prototype phase of those programs. Their numbers are too great to list here, and it would be unfair to single out any few individuals for special appreciation.

Despite this considerable assistance, the authors remain responsible for the conclusions of the study and for any errors or misinterpretations that may appear.

GLOSSARY

AAH	Advanced attack helicopter
ACF	Air combat fighter
ACM	Air combat maneuvering
AEFA	Army Engineering and Flight Test Activity
AFFE	Air Force flight evaluation
AFFTC	Air Force Flight Test Center
AFLC	Air Force Logistics Command
AFPRO	Air Force Plant Representative Office
AFSC	Air Force Systems Command
AFTEC	Air Force Test and Evaluation Center
AGE	Aerospace ground equipment
AMST	Advanced medium STOL transport
APU	Auxiliary power unit
ASARC	Army System Acquisition Review Council
ASD	Aeronautical Systems Division of AFSC
ATC	Air Training Command
AVSCOM	Aviation System Command
AX	Attack-Experimental
CAIG	Cost Analysis Improvement Group
CAS	Close air support
CPIF	Cost plus incentive fee
CPP	Competitive prototype phase
CE	Current estimate
DARCOM	Development and Readiness Command
DE	Development estimate
DSARC	Defense System Acquisition Review Council
DTC	Design-to-cost
DT&E	Development, test, and evaluation
ECP	Engineering change proposal
FFP	Firm fixed price
FLIR	Forward-looking infrared
FPIF	Fixed price incentive fee
FSD	Full scale development
GAO	General Accounting Office
GCT	Government competitive testing
GFAE	Government-furnished aerospace equipment

GFE	Government-furnished equipment
HUD	Head-up display
INS	Inertial navigation system
IOC	Initial operational capability
IOT&E	Initial operational test and evaluation
JTF	Joint Test Force
LCC	Life cycle cost
LOGO	Limitation of government's obligation
LWF	Lightweight fighter
MOU	Memorandum of understanding
MQT	Model qualification test
MTBF	Mean time between failure
OSD	Office of the Secretary of Defense
OTEA	Operational Test and Evaluation Agency
PNVS	Pilot's night vision system
PMO	Program manager's office
PFRT	Preliminary flight rating test
RAM	Reliability, availability, maintainability
RDT&E	Research, development, test, and evaluation
RFP	Request for proposal
RFQ	Request for quotation
R&M	Reliability and maintainability
SAR	Selected Acquisition Report
SAS	Stability augmentation system
SFC	Side force control
SPO	System program office
TAC	Tactical Air Command
TADS	Target acquisition designation system
TECOM	Test and Evaluation Command
UTTAS	Utility tactical transport aircraft system
WBS	Work breakdown structure

CONTENTS

FIGURES

TABLES

I. INTRODUCTION

The development of any new weapon system involves the accommodation of numerous uncertainties and risks. Some of these stem from the technological elements of the system, because most new systems require the developer to produce new components and higher performance levels. Other uncertainties stem from the fact that the development process typically takes five to ten years, and during that time the need for the system and how it might be used is likely to change. The developer will recognize some of the uncertainties and risks and can devise a plan that will tend to balance the risks against the resources available and the perceived urgency of operational availability. The developer also knows, from experience, that unforeseen problems will arise during the course of the project, and prudent managers make some kind of provision for coping with such events.

The particular management method selected for accommodating the various uncertainties and risks constitutes a major element of the overall development strategy. Many such strategies have been tried, each with a somewhat different set of underlying premises and a different balance between risks and costs. Selection of a "best" strategy has been debated vigorously for many years and is the subject of a voluminous literature. One critical issue in that continuing debate is the extent to which the various uncertainties (performance, cost, and operational suitability of the final product) can be satisfactorily resolved through analysis and design studies, or if it is actually necessary to build and test an example (a prototype)[1] to have sufficient confidence to proceed with the program.

Prototyping as a risk reduction strategy has alternated widely between acceptance and rejection by the USAF during the past few decades. Shortly after World War II, the dominant theme was one of a cautious, experimental approach, as the Air Force shifted from propellers and reciprocating engines to the jet age. During the late 1940s, 11 different fighter aircraft prototypes were carried to the flight test stage.[2] Four of those were subsequently put into serial production, and in two other cases the prototype provided technical information that contributed to the later development of another design that did go into production. That was clearly an era when both buyer and seller preferred to make major design and program decisions on the basis of flight demonstrations, and multiple competitive designs were frequently flight tested to select one design for service use.

During the 1950s, the USAF shifted its attitudes and beliefs concerning aircraft weapon system development. The exact reasons have been obscured by time, but the main themes can be discerned. One argument was that the old method of contracting for an "XF" or "XB" model, flight testing and modifying it, then contracting for a production article that might differ considerably from the original was inherently wasteful. It was sometimes hard to see how the prototype of a subsequently successful model had contributed to that success, and the prototypes of models subsequently canceled tended to be viewed as a total waste. This argument was strengthened by the belief that a major source of development risk was the integration of the various major subsystems in an aircraft (airframe, engine, fire control system, and weapons), and such integration could not be tested on anything short of a complete system.

---

[1]See Section II for a more thorough examination of what is meant by "prototype."

[2]These were the XF-84, XF-86, XF-89, and YF-94, each of which led to serial production; the XF-88 and the XF-92, which provided a technical base for subsequent development of the F-101 and F-102, respectively; and the XF-85, XF-87, XF-90, XF-91, and XF-93, which were canceled after prototype test.

Therefore, some people argued that a prototype consisting of only one or two subsystems was not likely to reduce development risk.

At about that same time analytical methods available to aircraft designers were undergoing major advances. Toward the end of the 1950s, digital computers became widespread and made possible a vastly more complex and exhaustive design analysis in support of each new development program than had previously been available. That capability led many designers to have greater confidence in their engineering predictions and to demand less in the way of preliminary flight tests to validate their calculations.

Another major factor contributing to the shifting viewpoint was the concurrent growth of systems analysis as a decision aid. Many practitioners of that new art form became persuaded that through analytical means they could examine many of the issues leading to the design specification of a new system and that such analysis was faster, more complete, and less expensive than the old practice of building and testing prototypes.

The result of these several concurrent advances and changes was the belief that a more efficient process would be to study the alternatives carefully, select one design for development, and make a production decision very early in the flight test stage so as to ensure the earliest possible introduction of the system to the operational forces. It was believed that a prototype phase would be unnecessary for most new programs.

Developments by the Air Force during the late 1950s and the 1960s generally followed that doctrine. In that period the Air Force initiated only a dozen major aircraft acquisition programs.[3] Four of those (F-106, F-5, YF-12, and KC-135) were extensions of previous designs and not truly new systems. Six programs (F-105, F-111, B-58, B-70, C-141, and C-5) were launched more or less directly into full scale development, with the single developer having been selected, and the design specification approved, on the basis of analysis and wind tunnel tests. In the most extreme cases (C-5, for example), the initial contract included a commitment to both development and production of the system. In other cases, high-rate production was authorized early in the test program. One program, the B-70, was plagued by uncertainties about its mission concept and eventually was scaled back to two flight vehicles.

Of the systems developed during that period, only the F-107 and the XC-142 went through a prototype stage, and both programs were canceled after test of two flight articles. The failure of those programs to proceed into full scale development further strengthened the belief that prototyping was not a sensible strategy.

During the 1960s a large management structure at OSD level was devised to control the development of new weapon systems, and a formal decision review process was installed. That process, which has survived to the present time in slightly modified form, has in almost all cases approved the design specification and the full scale development of a new system on the basis of analysis, design studies, and some limited tests of selected components. Even serial production of new systems has frequently been approved on the basis of only fragmentary tests of the development item.[4] The shift from prototype test to analysis as a basis for major management decisions has been almost total. Throughout this report we will refer to the common practice of the 1960s and 1970s as the "conventional" development approach, in contrast to the prototype approach.

Unfortunately, experience during the past two decades has not provided robust support

---

[3]During that time the Air Force also procured a large number of F-4s and A-7s, both of which were initially developed by the Navy.

[4]A more thorough description of the evolution of OSD management practices can be found in G. K. Smith and E. T. Friedmann, *An Analysis of Weapon System Acquisition Intervals, Past and Present*, R-2605-DR&E/AF, The Rand Corporation, November 1980.

for the notion that most risks and uncertainties in a new weapon system can be resolved by analysis. Some of the systems developed during that time period encountered major difficulties. Risks were sometimes underestimated or overlooked, and technical problems surfaced after substantial production resources had been expended, requiring extensive modification efforts or service acceptance of less than expected performance. Programs encountering such pitfalls (such as the F-111 and the C-5) suffered extraordinary cost growth. The other Services had similar problems, as exemplified by the AH-56 "Cheyenne" helicopter and the MBT-70 tank.

The end of the 1960s saw a regeneration of interest within many sections of the acquisition community in prototyping weapon systems as a means of resolving some of the risks before making major program commitments. Two governmental commissions, the General Accounting Office and a Defense Science Board Task Force, as well as The Rand Corporation, issued reports that favorably evaluated the idea.[5]

Those studies had to draw on experience that was growing old, because no major aircraft prototype programs had been undertaken after the mid-1950s. It became increasingly questionable if the experience of the 1940s and early 1950s was truly applicable to the more complex systems being developed in the 1960s and 1970s.

During the early 1970s, largely at the instigation of Deputy Secretary of Defense David Packard, several new weapon system development programs were designed to include a prototype phase. Those programs have now progressed to the point where their overall outcomes can be projected with reasonable confidence; they provide an opportunity to update our experience base on prototype acquisition practices and to reassess the merits of that strategy.

STUDY OBJECTIVES

We undertook this research to sharpen our understanding of the advantages and disadvantages of prototyping and of the conditions under which it might profitably be applied in today's environment. We examined four weapon system acquisition programs of the 1970s that had a prototype stage and compared those programs with a broad range of acquisition programs that used other acquisition strategies. We sought answers to two broad questions:

- Did the outcomes of the programs using a prototype stage differ in any significant and consistent way with other programs that had omitted a prototype phase? If so, what characteristics and attributes of the prototype phase contributed most to the beneficial outcomes?
- What specific lessons can be derived from those programs that can be applied to the acquisition of similar systems in the future? If a prototype phase seems appropriate, how should that phase be designed and managed so as to provide the greatest benefits to the overall program?

In addition, we attempted to document the individual case studies in some detail so that the information could be available to other researchers. The four programs selected for analysis were:

---

[5]See Blue Ribbon Defense Panel, *Report to the President and the Secretary of Defense on the Department of Defense*, Washington, D.C., 1970; *Report of the Commission on Government Procurement*, Washington, D.C., 1972; U.S. General Accounting Office, *Evaluation of Two Proposed Methods for Enhancing Competition in Weapons System Procurement*, B-39995, 14 July 1969; B. H. Klein, T. K. Glennan, Jr., and G. H. Shubert, *The Role of Prototypes in Development*, The Rand Corporation, RM-3467-PR, February 1963; Robert Perry, *A Prototype Strategy for Aircraft Development*, The Rand Corporation, RM-5597/1-PR, July 1972 (an earlier version was issued in 1968).

1. AX (YA-9 and YA-10)[6]
2. Lightweight Fighter (YF-16 and YF-17)
3. Advanced Attack Helicopter (YAH-63 and YAH-64)
4. Utility Transport Helicopter (UH-60 and UH-61)

REPORT OUTLINE

Section II presents an outline of the different kinds of prototypes, and of the various objectives that might be sought in a prototype phase. That section concludes with a description of the analysis procedure used in this study, a summary of the four prototype systems that were examined, and the sources of data on nonprototype programs that were used to compare with the outcomes of the prototyped programs. Section III summarizes the results of our research, and Section IV contains the conclusions. Four appendixes are attached, each devoted to a description of one of the case studies performed for this project.

---

[6]Throughout the report, we use the "Y" prefix as an unofficial notation to identify the prototype versions of the Northrop and Fairchild aircraft. The Air Force never officially adopted this nomenclature for the A-9 prototype, and only did so for the A-10 prototype one year after the conclusion of the competitive flyoff.

II. HISTORICAL PERSPECTIVE AND RESEARCH APPROACH

The analysis of prototyping as a development strategy is complicated by the many different definitions and interpretations of exactly what a prototype is and by the general difficulty of evaluating anything as complex as an acquisition strategy where many different, and sometimes conflicting, outputs are sought. Here, we will define the prototypes examined in this study, review the objectives that have been sought through use of a prototype phase, and summarize the historical arguments for and against prototyping. We will then discuss the evaluation process and the consequent research approach used in this study.

WHAT IS A PROTOTYPE?

In the development of any new item, no matter how simple, there are almost always a few "pre-production" examples assembled for test and verification purposes before routine production begins and finished items are delivered to the customer. In the broadest sense those pre-production items can be called prototypes; and under that definition almost every new product, and certainly every new weapon system, can be said to have gone through a prototype phase. When applied to the weapon system acquisition process, however, the term prototype usually carries a somewhat more restrictive definition. Even then, the term has several different applications:

1. A unit assembled and tested to learn about some technical design concept or (less commonly) to explore in some very preliminary way the operational characteristics of a radically new system concept. In aircraft systems, this kind of prototype is usually designated as an "X" item (X-15, X21, etc.) and has few, if any, of the trappings of a truly operational weapon system.
2. A preliminary version of a possible future weapon system, assembled and tested to resolve some issues before a commitment is made to additional phases of the acquisition. The extent to which the prototype is a complete (rather than partial) replica of the intended final system depends on the issues to be resolved, but the prototype is oriented toward satisfaction of an operational need, rather than to resolving purely technical design issues. In some cases there may be no commitment to complete development and procurement of the system, and the prototype would then be developed as a hedge against the possibility that a system of that type may be needed in the near future.
3. A "pre-production" prototype, tested to validate the detail characteristics of the final design before high-rate production is started.

In this study we will concentrate exclusively on type number 2 in the above list. This kind of prototype is configured to satisfy an operational mission, rather than to be a technical experiment, and it is intended to contribute to the resolution of issues more complex than just whether to proceed into high-rate production. Throughout the remainder of this report, unless specifically qualified, the term "prototype" will refer only to this type. By this selection we make no claim that the other two kinds should not be called prototypes—only that we are

restricting ourselves to an analysis of the attributes possessed by the second type. Just what those attributes are, and why we consider them worthy of analysis, is discussed below.

PROTOTYPE PHASE OBJECTIVES

Prototypes have been advocated as a way of achieving several distinctly different goals during the acquisition cycle, and the debate over the merits of prototyping is sometimes confused by the various participants having sought somewhat different objectives. It therefore is appropriate first to identify the uses for which prototypes have been advocated. Although the range of arguments presented in the literature is not amenable to precise categorization, we identify three different kinds of potential benefits.

Efficiency During Development

Much of the literature on prototyping emphasizes efficiency during development. The underlying assumption is that development of a new weapon system involves a large number of technical difficulties and that inevitably some things will go wrong. Furthermore, the developers do not even recognize some of those difficulties, so no matter how much analysis is devoted to the design, the first few items built will almost certainly have some flaws. The actual history of system developments completely and unambiguously supports this assumption. One approach for coping with this problem is to introduce a prototype phase early in the program, usually before proceeding to full scale development. Even though the prototype may not be exactly like the final system, many of the potential problems will probably be revealed. The developers can take corrective actions before starting the final system design, and frequently those corrective actions can be proof-tested on the prototype. Two kinds of benefits are expected to emerge from this process: (1) The acquisition will cost less, because fewer corrective actions will be needed after completion of full scale development and (usually) some production, where changes can be very expensive; and (2) the quality of the final product should be somewhat enhanced, because some of the flaws will have been eliminated.

As noted above, this use of prototypes has been extensively discussed in the acquisition literature. For example, Perry observed[1]

> a prototype is built in the expectation of change, and the expectation of change is its only substantial justification. The objective of building a prototype is to discover what changes are necessary.

Much of the debate over this use of prototypes revolves around an estimation of the number and extent of design problems likely to be revealed by testing a prototype (especially an austere prototype that is not a complete system) and whether a prototype environment really permits resolution of those problems any more quickly or at less cost than in a conventional development approach. At one extreme, discovery of a major design flaw as a result of an austere prototype phase permits a lower-cost corrective action than if the problem had been revealed only in full system test, after full production tooling had been installed and a number of items were being fabricated. At the other extreme, if only minor changes are needed as

[1] Robert L. Perry, *A Prototype Strategy for Aircraft Development*, The Rand Corporation, RM-5597-1-PR, July 1972.

a result of the prototype phase, the savings may not equal the cost of the prototype itself. Thus any analysis of prototype strategy should examine the kinds of problems found and make some assessment of the costs of the prototype phase.

There are some important institutional reasons why the development efficiency argument is not widely used by program officials. One inevitable consequence of the advocacy process that any new system must survive is that the proponents of the system tend to minimize the risks and uncertainties involved. Furthermore, advocates of a new system tend to dislike introduction of a prototype phase because some problems are sure to be revealed; and even though the problems are routine and easily corrected, they provide grist for arguments against continuing the system development. Finally, proponents of a new system see a prototype phase as a source of delay in achieving operational deployment.[2] Although these arguments are not amenable to quantitative analysis, they are important elements of any program design decision.

The use of *competitive* prototypes is sometimes advocated as an additional way to enhance efficiency during acquisition. Competition among industrial suppliers is widely considered to be desirable, and it is a common practice during the design phase when costs are small. However, full scale development and purchase of production tooling typically consumes 20 to 30 percent of total acquisition cost, so multiple competitive sources are rare beyond the start of FSD. This lack of competition beyond the study and proposal stages of a new program has long been a source of dissatisfaction among critics of weapon system acquisition practices.[3] Prototypes are often viewed as a way to extend a competitive posture further into the acquisition cycle at an affordable cost. Austere prototypes, usually consisting only of the basic flight vehicle, can usually be developed and tested for only 10 to 20 percent of the total FSD cost, thus making it feasible to retain a competitive posture through flight demonstration of the prototype. Almost every major weapon system prototype program conducted in this country in the past three decades has featured two competitive developers. Although the front end costs of such an approach are quite apparent (the full cost of the second, unsuccessful competitor), the benefits lie mainly in subjective arguments that competition makes each firm work more productively, increasing the quality or reducing the overall cost of the final product. We were unable to find any quantitative research that critically examined the cost/benefit balance of this strategy.

Improving the Quality of Decisions

The efficiency arguments discussed above were directed at a set of micro decisions, each dealing with a specific design problem. A typical development program involves many such decisions. There are also a few macro decisions, usually occurring at major program milestones and dealing with whether the program should proceed to the next phase. The risks and uncertainties inherent in a new system development project frequently dictate a sequential process, where the results of each phase would be validated and found acceptable before

---

[2] A quote from David Packard is illustrative:

> A few months ago at a meeting of military project managers, someone objected to extensive testing because it would delay the program. He complained that testing showed up things that needed to be fixed and it took time to fix them, and this would delay the initial operating capability. Unless we get rid of that kind of thinking there will be no hope.

"Improving R&D Management Through Prototyping," *Defense Management Journal*, July 1972.

[3] See, for example, K. Archibald et al., *Factors Affecting the Use of Competition in Weapon System Acquisition*, The Rand Corporation, R-2706-DRE, February 1981.

authorization was given to proceed with the next phase. A prototype is sometimes an appropriate way of accomplishing such validation. For example, one issue of the DODD 5000.2 stated:

> Comprehensive demonstrations are conducted to validate the design concepts and to provide a basis for selection of a system for full scale engineering development and subsequent production. *The demonstrations should be conducted with full scale prototypes in realistic operating environments when feasible and practical.*[4]

This use of prototypes usually emphasizes validating estimates of acquisition cost and schedule and selected hardware performance parameters. Perhaps the ultimate measure that should be validated is system value to the user, but the extensive operational utility tests that would be required for such validation are rarely incorporated in a prototype program.

One of the most obvious uses of a prototype phase is to provide a more confident basis for selecting among options. In actual practice, this has almost always turned out to mean *source selection* between two contractors who are competing for the same weapon system program. In most such cases, the competitors have both designed their models against the same mission specification, and the selection is made on the basis of demonstrated performance and projected future acquisition costs. That is, they offer different technical approaches toward satisfying a single operational concept.[5]

The arguments over this use of prototypes are largely on the question of just how much additional confidence one can have in estimates of future program outcomes through prototype tests and whether the services can effectively use that information. Opponents argue that little additional confidence is obtained, and the system is sure to evolve after the prototype phase, thereby partially invalidating prototype tests as a decision basis. An analysis of this strategy should therefore attempt to discover what kinds of unexpected information were obtained from the prototype tests, how timely that information was, and how those results affected the subsequent program decisions.

Hedging Against Uncertainties

Another way to accommodate uncertainty is to develop more than one option, thus hedging against the possibility that some of the options may encounter serious technical difficulties or turn out to be not fully responsive to the evolving threat. A quotation from an earlier study[6] summarizes this class of objectives:

> [One] advantage of the prototype approach is that for a given sum of money it is possible to have more programs underway at any given time, and hence we can cover a wider range of strategic contingencies. The initial commitment to a [full scale development and production] program is usually several times as large as that to a prototype program and thus reduces

---

[4]Department of Defense Directive 5000.2, *Major System Acquisition Process*, Office of the Deputy Director of Defense for Research and Engineering, January 18, 1977, paragraph IV.F.8.

[5]In theory, there is the potential of using prototypes in a somewhat different way—to test fundamentally different methods of satisfying a broad mission need. For example, a prototype fixed-wing airplane and a prototype helicopter might be pitted against each other in field trials to see which type best provided firepower support to ground troops (the close-air-support mission). There are occasional examples of a prototype being developed as a hedging alternative to an existing system (the Air Force LWF as an alternative to the heavier and more complex F-15, for example), but the authors are unaware of any examples of prototypes used directly and specifically to explore alternative solutions to a mission need at the major system level, or of any substantial body of analysis and debate regarding the merits of such an approach.

[6]B. H. Klein et al., *The Role of Prototypes in Development*, The Rand Corporation, RM-3467/1-PR, April 1971.

> correspondingly the number of different systems which can be investigated and the scope of the contingencies which can be faced. We have then, in a variety of prototype developments, a hedge against strategic uncertainty. . . .
>
> [Another] advantage of prototype programs is that they can provide a hedge against technological uncertainty. Thus having under development several alternative aircraft to perform a given mission or a group of missions means that there is a higher probability of achieving the desired capability.

One important aspect of this use of prototypes is that it may provide a way of starting some hardware work on a new system without first completing the rigorous and sometimes lengthy "requirements" review and validation process. Major General George Sammet, Jr., then Deputy Chief of Research and Development in the Office of the Chief of Staff, U.S. Army, said:

> prototyping [is] a device to allow industry and the Army to submit new concepts from their own in-house talents for possible funded support without the necessity of a matured formal Service requirement. In this case, the approach will be to build what, in effect, is an early "non-requirement" prototype that could conceivably enter the advanced or engineering development process farther downstream.[7]

This use of prototypes has received considerable attention and support from analysts of military procurement and force planning practices.[8] To measure its effectiveness and value, one would want to determine how many such programs had led to full system development (the option was adopted) versus the number that had been allowed to languish. However, there is little evidence that this idea has provided the main support for more than a handful of actual prototype programs. The XC-142 VTOL transport and the more recent Lightweight Fighter and Advanced Medium STOL Transport programs are the only aircraft examples that come to mind. Thus, the data base is very small, and evaluation difficulties are further compounded by the suspicion that if additional "option" prototypes had been developed, they might have led to successful systems.[9] Like the arguments about the value of competitive programs, this particular aspect of prototyping seems beyond the range of quantitative analysis but remains an important element of the overall theory of prototyping.

ANALYSIS METHODS AND OBJECTIVES

The objective of this study was to better understand the benefits and costs of a prototype phase, so that lessons from past experience can be effectively applied to the design of future acquisition programs and to the refinement of acquisition policy. The most satisfying way to achieve such an objective would be to compare the outcomes of prototyped programs with the outcomes of programs that did not involve a prototype phase. The underlying hypothesis here is that acquisition strategy has some significant effect on program outcomes, or at least some effect on development efficiency. But can we measure either effect?

First, consider the problem of evaluating an acquisition strategy in terms of how it affect-

---

[7] "Army Prototyping Philosophy: Improve the Acquisition Process," *Defense Management Journal*, July 1972.

[8] There is, however, some doubt that development of a system prototype in the absence of a firm, approved military requirement would be permissible under the guidelines of OMB Circular A-109, *Major System Acquisition*. Although that circular clearly supports the use of prototypes as a way of exploring alternatives, it also states that such alternatives "will be explored within the context of the agency's mission need and program objectives."

[9] A discussion of how options may be beneficial even if not exercised is contained in Anthony Downs, "The Value of Unchosen Alternatives," The Rand Corporation, P-3017, November 1964.

ed the outcome of the overall program. There are many elements to a program "outcome." The ultimate measure is the effectiveness of the weapon system in its assigned role, but such effectiveness is rarely measurable in a satisfactory way. We might argue that the operational life of a system, or the number procured, could be used as proxies for system value. However, those measures are surely affected by many external factors, and it seems unrealistic to think they were strongly influenced in most cases by the acquisition process.

An alternative approach is to examine the outcomes of the acquisition phase itself, and here two kinds of outcomes may be measurable. First, were the resource requirements (time and money) of one strategy consistently different from that of another strategy? That is, was one strategy more efficient than the other? Second, were the acquisition phase resources more predictable using one strategy rather than another? That is, did the sequential validation of estimates improve the overall predictability of the acquisition phase outcomes?

This second approach is the principal one used in this study: to compare acquisition phase resources consumed, and outcome predictability, of prototype programs with other acquisition strategies. Thus, we are attempting to evaluate the "efficiency" objective and, to a limited extent, the "decision quality" objective. However, within even this limited scope a caveat is needed. Prototyping is a strategy susceptible to many variations, but the number of actual prototype programs available for examination is quite small; and in many cases the effects of a prototype phase (either positive or negative) cannot be quantitatively measured. Consequently, wherever possible we go beyond a simple examination of program outcomes to examine the programs themselves in considerable detail, even if the results are only qualitative and inferential.

The study objectives can now be stated in a more concise (and more constrained) manner. When examining actual prototype programs we shall attempt to answer the following questions:

- What benefits were achieved? Did the prototypes yield information that greatly reduced some important risk or uncertainty or did they permit increased efficiencies in the overall acquisition process?
- What were the costs, in terms of dollar investment and time required?
- How did those cost and schedule outcomes compare with typical programs developed under other acquisition strategies?

Advocates of the prototyping strategy have long argued that special organization and management methods should be applied to maximize the benefit/cost ratio. Therefore we added another study objective:

- How were the projects organized and managed, and did that have any discernible effect on the program outcomes?

Research Design

Our approach was to examine in some detail a sample of prototype programs conducted during the 1970s. In selecting the sample, we wanted to cover at least two services (to test for service-specific acquisition policies) and to include programs where the prototype phase was designed to achieve different objectives. The final selection consisted of four programs:

1. AX (YA-9 and YA-10)
2. Lightweight Fighter (YF-16 and YF-17)

3. Advanced Attack Helicopter (YAH-63 and YAH-64)
4. Utility Transport Helicopter (UH-60 and UH-61)

For each program we conducted extensive personal interviews with project personnel both in the service and in the contractors' plants. Information was obtained in each of the following areas:

- The service requirements and program objectives, and the general institutional setting in which the program was conducted.
- The acquisition plan for the system at the beginning of the prototype phase, with particular attention to the objectives of the prototype phase and how that phase was integrated into the program.
- Outcome of the prototype phase, in terms of resources expended. information obtained from the prototype tests, and the schedule of events.
- The evolution of the program after the end of the prototype phase, with particular attention to how the prototype results affected subsequent events.
- The management methods and organizations used during the prototype phase and in the transition from the prototype phase to the subsequent phases.

Since one of the objectives was to compare the results of these prototype programs with comparable programs conducted without prototypes, a data base on other programs was also needed. For that we relied on data collected in other research projects[10] rather than on data collected specifically for this project.

To provide some context to help the reader interpret and understand the following discussion, a brief description of each prototyped system follows. A more complete description of each program is contained in the appendixes.

Attack-Experimental (AX)

One of the first major weapon systems developed under design-to-cost principles,[11] the AX competitive prototype program began in 1970 and culminated in 1972 with a flyoff at Edwards Air Force Base between the Northrop YA-9 and the Fairchild YA-10. After the flyoff, the Air Force awarded Fairchild a contract for full scale development that included extensive use of the two YA-10 prototypes until DT&E aircraft became available two years later.

The A-10 is a subsonic, single-place, twin-turbofan aircraft designed specifically to operate in close proximity to friendly ground forces against hostile targets such as protected personnel and armored vehicles. Production deliveries began in 1975 and continue today. The Air Force currently plans to acquire 727 production aircraft.

Lightweight Fighter (LWF)

In 1971, Deputy Secretary of Defense David Packard encouraged the Services to begin some advanced prototype programs to demonstrate design concepts and advanced technolo-

---

[10]The major source of comparison data was Edmund Dews et al., *Acquisition Policy Effectiveness: Department of Defense Experience in the 1970s*, The Rand Corporation, R-2516-DR&E, October 1979.

[11]In a design-to-cost strategy, a target cost is established for the final production article and the designer seeks the greatest level of system performance without exceeding that production cost. This is distinctly different from the more usual practice of specifying the system performance and then trying to minimize the cost of a design that achieves the specified performance.

gies before start of full weapon system developments. Each service nominated several candidates to be funded by a new budget Packard set aside for that express purpose. One that was approved was the Air Force Lightweight Fighter program, designed to demonstrate the uses of advanced materials and design concepts in a small, low-cost, highly maneuverable day fighter. Two designs, the General Dynamics YF-16 and the Northrop YF-17, entered flight test early in 1974. The test program initially emphasized evaluating the various design concepts, since there was no commitment or plan to further develop either version into a full weapon system.

During 1974 the Air Force, with strong OSD encouragement, decided to complete the development and procure the system for the Tactical Air Force, and several European countries expressed interest in buying such an airplane. In August 1974 both companies were awarded transition contracts to cover the additional work needed to turn the technology development program into a weapon system competition. In January 1975 the Air Force selected the F-16 and awarded a full scale development contract to General Dynamics. In June 1975 the United States and a consortium of European nations signed an MOU calling for joint production and procurement. The first operational models were delivered to the USAF late in 1978.

Advanced Attack Helicopter (AAH)

Soon after the Cheyenne program was canceled in 1972, the Army initiated a search for a lower cost and lower risk alternative. The AAH program was started in 1973 with the objective of developing a fully integrated system (airframe, weapon, and sighting system) that could be produced for just over half the projected cost of the Cheyenne. A competitive prototype program was initiated, but the need to hold development cost down dictated that the extra contractor not be carried the full length of the program. The Army divided the program into two phases: a competitive first phase during which two contractors would pursue the more difficult and risky airframe/engine development; and a sole-source second phase during which the winning contractor would integrate the aircraft's main armament, the TOW antitank missile system, into its airframe. Phase I was scheduled to take about three years, and the second phase was expected to consume two more years. Only after five years of extensive prototype development and testing would a decision be made to produce the new system.

Development of the Bell YAH-63 and the Hughes YAH-64 prototypes began in 1973. At the end of the prototype phase the Army awarded Hughes a contract for further development of the AH-64. At that time the Army specified major changes in the weapon system, substituting Hellfire for TOW and adding a new weapon sighting and night vision system. Those changes extended the schedule, and production start date is now uncertain.

Utility Tactical Transport Aircraft System (UTTAS)

A major objective of the UTTAS program was to develop a helicopter that would be easier and cheaper to maintain than the Army's existing utility helicopter, the UH-1. To obtain credible reliability and maintainability statistics from the prototype tests, the Army conducted a competitive prototype program where both sources developed a complete and fully oper-

ational design; the winner was then awarded a production contract. Boeing Vertol and Sikorsky started development in 1972, with each contractor producing three flight test articles. After a total of nearly 3000 flight test hours, the Army selected the Sikorsky UH-60 in late 1976 and began the production phase.

III. RESEARCH RESULTS

While evaluating the four prototype projects considered in this study, we will be comparing the benefits obtained from the prototype phase with the costs of that phase. To make such a comparison, it is useful to first determine the benefits that were sought. Some programs may never achieve a potential benefit simply because it was not considered important to that particular program and was not sought. We will therefore also identify some other results of the prototype phase, even if they were not part of the original acquisition strategy.

PROTOTYPE PHASE OBJECTIVES

What were the program managers and designers trying to accomplish by inserting a prototype phase? In actual practice most system development programs have a mix of objectives, some considered more important than others. We attempted to identify both primary and secondary objectives of the prototype phase in each of the four subject programs, as shown in Table 1. The "primary" goals are believed to be those that provided basic justification for inclusion of a prototype phase. The value of the prototype phase should be measured primarily in terms of how well those goals were met. Although the secondary goals are important and of potential value, they should be considered bonus items.

Table 1

GOALS OF THE PROTOTYPE PHASE

Goal	AX	LWF	AAH	UTTAS
Efficiency during development	o	o	-	-
Enhance use of competition	o	o	o	o
Improving quality of decisions				
Validate production cost	x	-	x	o
Validate operating cost	x	-	-	x
Validate system performance	o	o	o	o
Source selection	x	x	x	x
Hedge against uncertainties				
Mission need	-	x	-	-
Development failure	-	-	-	-

x = primary goal
o = secondary goal
- = not an important goal

Even the retrospective assessment of such primary and secondary program goals is remarkably difficult in some cases because program documents rarely make such a characterization. The assessments here reflect our own judgment, based on the environment at the start of the prototype phase and on the subsequent design of the program.

PROTOTYPE PHASE BENEFITS

Measured against the general goal structure outlined above, how well did the prototype phase of the several programs perform? A summary of results is presented below, and additional details are contained in the appendixes.

Efficiency During Development

In any new weapon system development program the test phase reveals a number of deficiencies, some minor, some major. There is inevitably a maturation phase where those deficiencies are identified, the design is changed, and the new configuration is tested. A prototype phase offers an opportunity to conduct that maturation process more efficiently if two conditions are met. First, some time must be allowed to conduct the test-redesign-retest process. Since that may take many months, the maturation process must occur mainly while the program is still in a rather austere phase, otherwise the expense of extending the program becomes prohibitive. This certainly means that most of the maturation process must occur before the production-oriented design and tooling work begins. Second, the prototype must be a reasonable approximation of the expected final design, so that the lessons learned from the prototype tests can be expected to apply to subsequent phases of the program. Any major configuration change between the prototype and subsequent full scale development design will probably negate many of the maturation lessons learned from the prototype.

Apparently none of the four prototype programs was organized with the intent to capitalize on the inherent opportunities for efficient design maturation. Three of the programs (AX, AAH, and UTTAS) were widely characterized as being "conservative" in the levels of performance sought, and in no case did the projected schedule allow specifically for test-redesign-retest activities that would indicate some expectation of design change as a result of the prototype phase.[1] Furthermore, both helicopter prototypes were designed with standard, full scale engineering development methods, eliminating any opportunity for low-cost correction of design problems revealed during tests. Nevertheless, benefits were obtained to varying degrees in each program.

LWF Program. Although it was not clearly stated as a program objective, the LWF program benefited in terms of *efficient* design maturation because of several special program characteristics. The most important of these was that when the prototype phase was organized, and throughout most of its duration, there were no specific plans or programs for follow-on FSD and production phases. Furthermore, neither contractor was contractually obligated to meet any specified level of system performance. This created a remarkable environment where many of the problems that did arise could be corrected rather quickly. Both Air Force and contractor personnel could work at their own schedule, and if something seemed important they could stop and fix it before proceeding with the test. No ECPs were needed, only a quick verbal agreement among the executives who were usually on the spot at Edwards AFB. Furthermore, Air Force and contractor personnel had a common goal of identifying problems and finding quick and suitable solutions. The existence of true competition clearly enhanced that process. This is in marked contrast to a sole-source FSD program, where every move is controlled by the contract, the interests of the Air Force and the contractor frequently diverge, and the program is scheduled so tightly that any time allocated to fixing a problem can have large cost consequences.

---

[1]In all three programs, the prototypes of the winning contractor were used extensively to flight test design changes during the subsequent full scale development phase.

Four areas of design maturation in the LWF prototype phase seem particularly noteworthy: The novel fly-by-wire control and autostabilization system underwent many refinements, and its acceptability was fully validated; changes were made to the fuel control unit on the engine to minimize flameouts; experience showed that some uses of composite materials were unwarranted, and other uses were proved valid; and a special team of maintenance experts supplied by the Tactical Air Command recommended numerous refinements in maintenance access and component placement. Additional details on these topics are supplied in Appendix B.

A second important characteristic of the LWF program was that when the FSD phase was initiated, rigorous controls were imposed to minimize configuration changes from the prototype. Only three significant changes occurred: Mission avionics were added, the fuselage was extended 10 in. so that both the single and two-place versions could be built within a common fuselage shape, and the wing and tail were enlarged slightly to retain aerodynamic performance at increased gross weights. The aerodynamic consequences of the external configuration changes could be predicted with high confidence on the basis of prototype flight test results.

The effectiveness of the prototype-phase design maturation can be seen in the remarkable lack of subsequent problems with the FSD configuration *in areas covered by the prototype configuration*. The only new problem with the basic flight vehicle that was revealed during the subsequent FSD test phase was in recovery from stall at very high attitude angles, a flight region that had not been tested during the prototype phase. Several problems were experienced in the integration and operation of the mission avionics, but those elements had not been prototyped. The experience with the flight vehicle maturation during FSD is in marked contrast to that of other recent aircraft that were not prototyped, such as the F-15 and the F-111.

AX. A substantial degree of maturation occurred in the design of the basic flight vehicle during the AX prototype phase, even though the institutional environment was slightly different than in the LWF program. Here the prototype flight test phase was mainly an input to the source selection for the subsequent FSD phase; consequently, the participants had somewhat less freedom to modify the vehicle configuration as problems arose. However, YA-10 flight tests revealed four major design problems: (1) The engines suffered from inlet airflow distortion at high angles of attack, necessitating a redesign of the wing root leading edge; (2) unexpectedly high aerodynamic drag led to numerous design changes; (3) pilot dissatisfaction with the cockpit layout led to rearrangement of some controls and a change in the ejection seat; and (4) changes were found necessary in the stability augmentation system. FSD flight tests revealed that some of those same problems remained, although usually to a diminished degree. The drag problem had not been completely cured, nor did the pilots judge the stability augmentation system fully satisfactory.

Few changes were made in the configuration between the two phases: cockpit pressurization was added, an internal auxiliary power unit was installed, wing span was lengthened, and there was a change in the refueling receptacle design. None of those modifications led to subsequent problems. A new problem was revealed when the 30-mm gun (unavailable during the competitive prototype phase) was installed in the prototypes for testing during FSD. Changes to both the airframe and the ammunition were necessary to ameliorate the effects of gun gas ingestion into the engines. That problem was the only major new difficulty encountered during FSD. Thus it is believed that the prototype phase, as well as satisfying the basic objectives of performance and cost validation and source selection, did contribute to design maturation.

UTTAS and AAH. It is not clear that either of these programs benefited greatly from prototype-phase design maturation because in each case the prototype phase was organized like a competitive full scale development program. There was little opportunity for *efficiently* identifying and solving design problems. It is certainly true that design problems were identified during the prototype phase of each program. For example, during the UH-60 prototype tests changes were made to the transmission lubrication system, the stability augmentation system, the tail design, and the rotor fabrication method. Similarly, during the AH-64 prototype tests, changes were made in the rotor hub and tail configuration to improve lateral stability, and the rotor mast was lengthened in an effort to reduce vibration levels. The efficiency and alacrity with which these changes were made may have been enhanced by the competitive environment, but otherwise they appear to have been performed similarly to the changes that inevitably occur in any routine development program.

Development Efficiency Summary. The LWF program and, to a lesser extent, the AX program were organized in a way that permitted efficient design maturation during the prototype phase. There is some evidence that such design maturation did occur, based on the fact that problems were revealed and solved during the low-cost prototype phase and that a small number of new problems surfaced during the subsequent FSD phase. The two helicopter programs were organized in a way that reduced the opportunity for any unusual efficiency in design maturation.

Use of Competition

The use of competition in weapon system acquisition has long been advocated, but true competition beyond the planning stage is discouraged because development cost is typically a fourth to a third of the total acquisition cost. Extending competition through the development phase of a new weapon system might increase the apparent cost of the system by 20 to 30 percent, which is generally considered unacceptable.[2] However, an austere prototype phase offers an opportunity to extend competition part way through development at an acceptable cost, and all four of the systems reviewed in this study did have two competitive sources throughout the prototype phase. The actual costs are summarized later in this section; here, we are interested in determining the benefits (if any) of that competition.

It was clearly not possible to measure the effects of competition quantitatively since there were no noncompetitive "control" programs. However, we discussed the competitive aspects of the programs at length with management personnel in all four of the Service Program Offices. That survey revealed one area of differing viewpoints and one area of consensus. The difference was between the views of the Army and the Air Force managers on the kinds of benefits to be sought from competition. The two Air Force programs conducted the prototype phase on the equivalent of a firm fixed price basis with few contractually specified deliverables; the system program manager had a very small staff during the prototype phase, relying instead on the competitive environment to ensure that the contractors performed effectively. The Air Force managers uniformly believed that the arrangement had been highly successful. Conversely, the Army prototype programs used detailed contracts and extensive Program Office staffs, and the opportunities were reduced for exploiting the competitive environment as a substitute for Project Office management controls over the contractors.

---

[2]Advocates of competition argue that the benefits of competitive development may still be worth the cost, but those benefits are difficult to measure and development funds are so limited that competitive complete development of a major weapon system is rare.

Nearly everyone agreed that the contractors were more responsive to Program Office direction while in a competitive environment than they were after entering into the sole-source phase of the program. This effect cannot be measured in any practical way, but it might still be an important source of benefits. A sole-source contract covering development of a new weapon system is a large and complex document, and any major deviation from the planned development program can lead to complex, time-consuming negotiations. Such deviations are inevitable during the development phase, and sometimes the course of the program is influenced by the mechanics of contract modifications rather than the technical problems alone. In a competitive environment those problems are reduced because the industrial teams are highly motivated to satisfy the client and normally have a more flexible contract environment. Many experienced managers believe that the efficiencies resulting from a competitive environment during a part of the development phase could exceed the direct costs involved.

Cost Validation

Validation of acquisition or operating cost estimates was a major goal in three of the programs. In the AX and AAH programs strict DTC goals were established in terms of allowable production cost of the final design, and the prototype program was considered to be an important step in gaining confidence, by both the producer and the buyer, that the design finally selected could satisfy the cost goals. In the UTTAS program a critical design objective was an operating cost lower than that of an equivalent fleet of UH-1s, and the prototype program emphasized demonstrating the desired levels of component reliability and maintenance manhours per flying hour through an extensive test program.

When the LWF program was started there was no official expectation of any full scale development or production phase, nor were any production cost goals stated in the prototype phase documentation. However, the existence of prototype phase experience might reasonably be expected to contribute to improved estimates of cost for subsequent phases.

Our objective in this analysis is to determine whether the cost growth experienced by those programs was different in extent from the average of other, nonprototyped programs and to identify the sources of any such differences. Unfortunately, cost growth in an acquisition program usually results from a combination of factors, and sometimes it is difficult to isolate the effect of any one set of factors.[3] What *is* clear is that the cost of each program has, in fact, exceeded the goals established at the beginning of full scale development, as shown in Table 2. The current estimate of total program cost (as of September 1980) is compared with the development estimate made at the beginning of full scale development. The UTTAS/UH-60 program is different from the others because there the DE was established at the beginning of the prototype phase, which was also equivalent to FSD. Thus there were no prototype results yet available when the DE was established. In the other three programs the DE was established after the prototype phase was well underway and presumably benefited from the results of the prototype work completed up to that time.[4]

---

[3]Throughout this analysis we use cost growth data published in the Selected Acquisition Reports, where cost growth is categorized according to several possible causes. See DOD Instruction 7000.3, *Selected Acquisition Reports*, for an explanation of the cost growth categories. Cost growth due to changes in performance specifications made after development starts (a historically important source of cost growth) should be fairly insensitive to the existence of a prototype phase.

[4]Lower cost growth does not necessarily mean money was saved. It could stem from a better (higher) estimate of the actual cost, thereby increasing the denominator of the CE/DE ratio.

Table 2

PROGRAM COST GROWTH RATIO,
CURRENT ESTIMATE/DEVELOPMENT ESTIMATE[a]

System	FSD Phase	Production Phase	Total
AX/A-10	1.27	1.28	1.28
LWF/F-16	1.28	1.18	1.19
UTTAS/UH-60	1.08	1.08	1.08
AAH/AH-64	1.12	1.11	1.11

[a]Current estimate of total program costs as of September 1980, adjusted to DE quantity. Prototype phase costs included in FSD and Total ratios for all programs except LWF. All values adjusted to constant dollars.

There are at least three ways in which the existence of a prototype phase might improve the ability to estimate future program costs, or to control subsequent cost growth—an improved data base for estimation, fewer unexpected configuration changes, and use of fixed price contracts.

Improved Data Base for Estimation. As a development program evolves and more information becomes available, the methods used for estimating the cost of future phases change. Early in a program simple parametric methods are used. As system design information is generated, more detailed and specific estimates become possible. Finally, after some units have been fabricated, the actual cost of labor and material is used to further refine estimates for future lots.

Some analysts contend that the existence of flying hardware permits better estimates to be made of the subsequent aircraft to be produced in the acquisition program. In the LWF program, General Dynamics used data on their prototypes as the basis for detailed cost estimates for the FSD and production phases. Although it was known that the production aircraft would be built with different materials, by different manufacturing methods, and with more complex tooling, GD industrial engineers and cost analysts attempted to use the prototype parts as analogs to better visualize what the mission aircraft would require and how each individual part would be made. A piece-by-piece cost buildup gave the GD management an estimate of the labor hours, material costs, and tooling that would be required to build their aircraft model using production line methods. Although this might be viewed as a clear advantage for the prototype acquisition concept, it is not the only way to derive such production cost estimates. For example, some Air Force cost analysts argue that the very detailed mockup of the F-15 aircraft provided essentially the same information for McDonnell Douglas cost analysts as the F-16 prototype provided for the GD cost analysts.

To the extent that the mission aircraft continues the same design configuration as the prototype (or mockup), either approach should be able to perform the analog function. And yet, the confidence in the estimates would not be the same for both approaches. There is a subtle but important difference: Whereas the F-16 prototype model had actually flown and its

performance had been evaluated and approved, the same could not be said of the F-15 mock-up. Much was unknown of the latter vehicle that could have seriously altered the costs further down the line. True, the F-16 experienced a number of small changes in converting from the prototype to the mission configuration, and further changes occurred in the F-16 design after full scale development began. But the initial hurdle of verifying that the basic aircraft would perform as specified had been passed, and the unknowns were consequently of more manageable proportions.

The SPO benefited from the improved cost estimating process only indirectly—by having greater confidence that *the manufacturer* was capable of producing a better cost estimate. The number of Air Force personnel who could devote themselves to cost analysis in the F-16 SPO was too small to take advantage of these "grass roots" cost estimating techniques, and they continued to make their estimates by means of parametric cost models. Such parametric estimates are not materially improved by the presence of a prototype except to the extent that aircraft weight—one of the primary independent variables of the cost models—is more accurately known after the prototype has been built and tested.

Since we lack a basis for direct comparison, we must compare the results of aggregate sets of programs. In Table 3, drawn from SAR records, we show the "estimation error"[5] for six nonprototyped aircraft development programs that have gone into the production phase, and compare them with the prototype programs. After we adjusted for inflation, the average estimation error of prototype programs was only slightly smaller than the average of other programs.[6]

Table 3

COST GROWTH DUE TO ESTIMATION ERRORS, ENGINEERING CHANGES, AND ALL CAUSES[a]

System	Cost Growth Ratio (CE/DE)		
	Estimation	Engineering	All Causes
Nonprototyped Programs			
E-2C	1.10	1.08	1.32
P-3C	1.04	1.11	1.22
F-14	1.08	1.01	1.43
E-3A	0.90	1.02	1.20
E-4	1.17	1.04	1.67
F-15	0.96	1.04	1.25
Average	1.04	1.05	1.35
Prototyped Programs			
AX/A-10	0.94	1.09	1.28
LWF/F-16	0.97	1.06	1.19
UTTAS/UH-60	1.16	0.99	1.08
AAH/AH-64	1.02	1.01	1.12
Average	1.02	1.04	1.17

[a]All data drawn from Selected Acquisition Reports, September 1980. CE adjusted to DE quantity as required. All values adjusted to constant dollars.

[5]Those unfamiliar with SAR cost reporting methodology should consult Department of Defense Instruction 7000.3.

[6]By December 1980, the UTTAS estimation error had grown to 1.24, making both series equal.

Fewer Unexpected Configuration Changes. A major source of cost growth is the need to change the configuration to correct for an unexpected technical difficulty. It has been suggested that a prototype evaluation before FSD might reduce the number of corrective design revisions that characterizes most aircraft development programs. The rationale is that the flying prototype test bed will reveal most of the design changes necessary to attain the desired performance and that these can be incorporated into the first full scale development aircraft as a block change. For example, Table 4 lists the major changes that occurred between the YF-16 prototype aircraft and the F-16 mission configuration. Some of these were corrections of deficiencies revealed by the prototypes, some were additions that had always been foreseen as necessary to transform the prototype into an operational configuration, and some probably reflected recent interpretations of operational needs. Weapon systems whose viability rests in large part on the weapons, tactics, and developments of a potential adversary obviously are subject to continuous update. It is impossible to predict the cost of these unforeseen requirements that may surface during the development and procurement period, but failure to allow any contingency funds for the seemingly inevitable upgrading has tended in the past to lead to program cost growth. This constant update process is visible in the F-15 and A-10 programs, and it is becoming evident already in the F-16 program as well; having a prototype program is no insurance against this update form of design change.

Table 4

F-16 CHANGES FROM THE PROTOTYPE CONFIGURATION

Emergency power unit modified and relocated
Ejection seat changed
F100(3) production engine substituted
Horizontal tail resized
Tail hook added
External stores capability expanded
Wing area expanded 20 sq ft
Fuselage length extended 10 in.
Landing gear strength increased
Blow-in doors deleted
Maintenance access provisions improved
Missionized avionics added

SOURCE: DSARC III Briefing, 11 March 1975.

Unfortunately, readily available program financial records do not permit separating "technical problem" changes from design and configuration changes caused by all other sources. As a first approximation, we can compare the totality of cost changes charged to "engineering" in the SAR records. Such a comparison is included in Table 3. On the average, programs with a prototype phase experienced nearly the same cost growth from this source as the average of other programs of comparable maturity. Furthermore, cost growth due to estimating error and engineering changes tends to be a small part of the overall system cost growth.

Use of Fixed Price Contracts. Prototyping may contribute to cost control by enabling more extensive use of fixed price contracts. Such contracts can be used for the prototype phase

itself, especially if competitive sources exist and deliverables are on a "best effort" basis. More important, it is frequently argued that a prototype phase produces enough information about a new design that all subsequent work can be conducted under a fixed price contract, thereby further restraining cost growth.

The actual effect of such a contract form is impossible to measure in such a small sample (see Table 5). The two Air Force prototype programs were firm fixed price[7] and the cost to the government was exactly the contract amount (zero cost growth), although the contractors may have contributed some of their own funds. Only the LWF program had a fixed price contract for the FSD phase, and all four programs used fixed price contracts in the initial production phases; but all programs experienced cost growth despite such contracts (see Table 2).

Table 5

CONTRACT TYPE

System	Prototype	FSD	Production
AX/A-10	FFP[a]	CPIF	FPI(F)[b]
LWF/F-16	CPIF[c] + LOGO[d]	FPI(F)	FPI(F)
AAH/AH-64	CPIF	CPIF	FPI(F)
UTTAS/UH-60	CPIF		FPI(F)

[a]Firm Fixed Price contracts involve an agreed-upon price before contract award, and price is not subject to any later adjustment.

[b]Fixed Price Incentive contracts with Firm Targets provide for an adjustment to profit based on the ratio of final negotiated costs to target costs. Contractor incentive to reduce cost is not as great as in FFP contracts.

[c]Cost Plus Incentive Fee contracts provide for cost reimbursement, plus a fee based on the difference between final and target costs.

[d]Limitation of Government's Obligation.

Cost Validation Summary. The data discussed above are summarized in Fig. 1. Here we show the two sources of cost growth that might be expected to be influenced by data from a prototype phase, together with total cost growth due to all causes, and compare the average results of the four prototype programs with the average results of six other contemporary aircraft acquisition programs that were not preceded by a prototype phase. The prototyped programs exhibited lower cost growth due to each separate cause, as well as lower total cost growth.

One problem with comparisons of this type, where the current estimate of program cost is compared with the development estimate prepared at the beginning of full scale development, is that cost tends to grow over time; and the older, more mature programs will tend to exhibit higher cost growth than will younger programs. To accommodate this problem the cost growth data are displayed in Fig. 2 as a function of time since start of FSD. Comparable data for the six nonprototyped aircraft acquisition programs are shown for comparison. The average of 27 major acquisition programs of the 1970s (including systems other than aircraft)

[7]The LWF program used a combination of a CPIF contract plus a LOGO clause, which has many of the same features as a fixed price contract. See Appendix B for a discussion of this contract form.

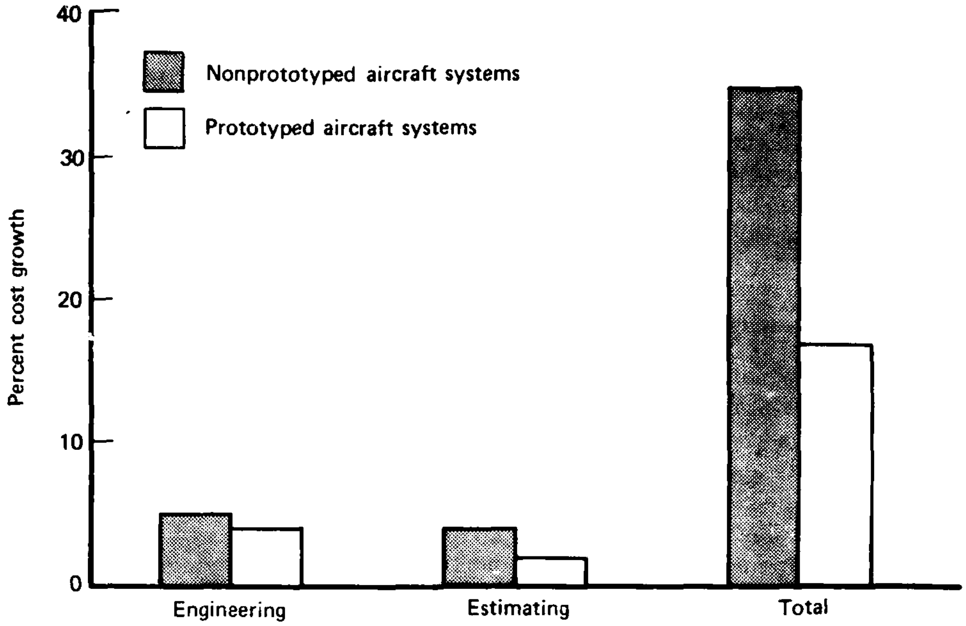


Fig. 1—Sources of cost growth

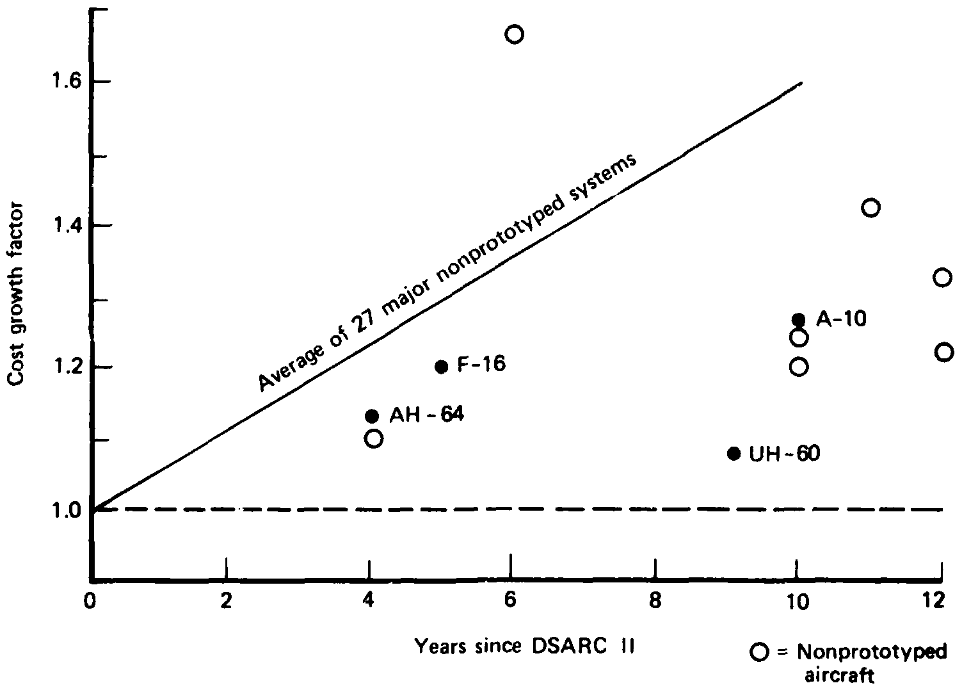


Fig. 2—Program cost growth

that did not use a prototype phase is also shown.[8] The prototype programs appear to have experienced somewhat less cost growth than the other programs, but conclusions must be tempered by the small sample size and the substantial amount of scatter from one program to another in either sample.

In two of the programs (AX and UTTAS) the operating cost was an important design goal. It would be desirable to compare the actual operating cost with the development estimate, but the complexities of measuring actual operating costs made such a validation beyond the scope of this study.

System Performance Validation

One of the most obvious benefits that might be obtained from a prototype program is the validation of at least some system performance capabilities. However, in none of the cases examined does it appear that there was serious uncertainty about achieving most of the system performance goals. This is clearly true in the AX, AAH, and UTTAS programs, as evidenced by repeated statements by program proponents that no significant technical risks were involved and that performance goals were clearly secondary to cost goals. In the LWF program the performance goals were much more ambitious, but that program was not structured as a precursor to a specific weapon system so it is not fair to measure its success in terms of performance goal achievement. Although validation of system performance was apparently not a dominant objective in any of the programs examined here, such validation did represent a large portion of the prototype testing programs and may have played an important role in the subsequent source selection proceedings.

Generally, prototypes are designed to test the basic flight vehicle, leaving most of the avionics and armament systems to be developed and evaluated separately. Three of the four programs reviewed in this study followed that approach; but one, the UTTAS, was nearly a complete, pre-production configuration, allowing a more complete validation of the full system performance.

The amount and value of performance validation information obtained from a prototype depend, in part, on the kind and extent of design changes introduced between the prototype and the final operational system configuration. In the usual situation where the prototype is an incomplete and austere version of the operational system, the real objective is not to learn how the prototype performs, but to use the prototype test results to project, with high confidence, the performance of the subsequent operational system configuration. In evaluating this aspect of prototype benefits we need to review the performance goals of the prototype, the prototype performance test results, any subsequent modifications in performance goals for the full operational system configuration, and the actual performance achieved by the operational configuration. We will first review that sequence for each of the four programs and then present some summary evaluations.

AX Program. The performance goals established for the AX prototypes, the performance demonstrated by the winning model, the revised goals established at the beginning of FSD, and the actual operational design performance achievements are shown in Table 6. It can be seen that in some cases the prototypes fell short of the goals, and in some cases the goals were exceeded. Based on the prototype test results, some changes were made in the performance

[8]Comparison data drawn from Edmund Dews et al., *Acquisition Policy Effectiveness: Department of Defense Experience in the 1970s*, The Rand Corporation, R-2516-DR&E, October 1979.

Table 6

AX/A-10 PERFORMANCE

Parameter	Prototype Goal	Actual YA-10	FSD Goal	Actual A-10A
Speed (kn)				
Maximum, level flight, 5000 ft, 6 bombs	350	N/A	385	368
Maximum, level flight, clean, SL	400	350	390	368
Cruise speed at 5000 ft	300	281	325	342
Maneuverability, 5000 ft alt (gs)				
Sustained load factor, 150 kn	2.2	2.2	2.4	2.0
Sustained load factor, 275 kn	3.5	3.0	3.5	3.2
Instantaneous load factor, 300 kn	5.0	5.8	6.5	5.7
Airport performance (ft)				
Takeoff ground roll, fwd airstrip wt	1000	1240	1050	1900
Takeoff ground roll, maximum wt	4000	3660	3660	4850
Landing ground roll, fwd airstrip wt	1000	1050	1050	1460
Landing ground roll, maximum wt	4000	2600	2600	4000

specifications for the full scale development phase of the A-10, and the final operational configuration again sometimes exceeded those revised goals and sometimes fell short. In some cases the FSD goal was clearly adjusted to bring it into line with prototype test results (maximum-weight takeoff roll distance, and forward-airstrip landing ground-roll distance), but in other cases the FSD goals were apparently set with little regard for prototype results (cruise speed at 5000 ft altitude, for example). Despite these minor variations, the prototype test demonstrated a flight vehicle capability that was deemed sufficiently good to warrant continuation of the program.

LWF Program. A similar comparison is not possible for the Lightweight Fighter program because no specific performance goals were established for the prototype phase. The contractor was obligated only to provide his best effort, guided by instructions on which kinds of performance would be deemed most valuable.

The value of the prototype YF-16 tests in terms of validating flight performance predictions can best be illustrated by the lack of unexpected flight performance problems during full scale development. Availability of prototype test data permitted the design engineers to validate performance prediction models, increasing confidence in predicting the performance changes resulting from the small configuration changes introduced between prototype and FSD phases. During the full scale development flight test, only one important flight vehicle performance problem was revealed—stall characteristics at very high pitch angles. That flight regime had not been explored during prototype tests and was therefore not anticipated.

UTTAS Program. The prototype phase was unusual in that the major performance objectives were in the area of maintenance and support costs, rather than flight performance. Some of the flight performance goals were stated as bands of acceptable performance, whereas the maintenance goals were much more specific. The prototypes were also unusual in that they were almost fully developed systems, leaving little additional development to be completed after the end of the prototype phase. Thus we are able to compare the prototype phase goals directly with the actual performance of the operational system.

Such a comparison is shown in Table 7. In general, the final operational configuration met the performance goals established at the beginning of the prototype phase, with the exception of the vibration level. Prototype tests suggested that the desired level of 0.05 g would be exceedingly difficult to achieve and the specification was relaxed to 0.1 g when the final source selection was made for the production phase.

Table 7

UTTAS PERFORMANCE GOALS AND UH-60
DEMONSTRATED CAPABILITIES

Performance	Prototype Goals	UH-60 Demonstrated
Rate of climb, ft/min (4000 ft altitude, 0 airspeed)	450-550	450
Speed, kn	145-175	145
Payload (number of troops)	11	11
Endurance, hr	2.3	2.3
Vibration level, g	0.05	0.1

The most important design objectives of the UTTAS program were in the area of system reliability and maintenance. Unfortunately it is not practical to compare initial specifications directly with final achieved performance in these areas because of the difficulty of measuring actual achieved performance under realistic operational conditions. All of the information available suggests that the UH-60 has generally met the objectives in these areas, even though they were exceedingly stringent.

AAH Program. Like the UTTAS program, the AAH prototype phase was designed to produce a basic flight vehicle that was nearly fully developed, including production engineering and compliance with military specifications. After the prototype phase was completed and a single contractor selected, the only remaining work was expected to be the integration of the weapon system into the proven flight vehicle. Despite this approach, the performance specifications issued to the prototype designers were sparse. The main characteristics are summarized in Table 8. In some cases (such as airspeed and endurance) the specified items were to be treated as minimum required capabilities, with greater performance being desirable. At the end of the prototype phase the AH-64 had demonstrated the capability of meeting all of the basic flight vehicle performance specifications except for endurance, which was slightly under the objective of 1.9 hours. However, the desired level of airframe vibration had not been achieved, and additional work toward that goal was continued well into the subsequent development phases.

Performance Validation Summary. Although much of the prototype test programs was devoted to evaluating the flight performance of the basic vehicle, few surprises were found. In all except the LWF program, the specified flight performance was considered well within the current state of art, and results proved that generally true. In a few cases the prototype test results led to modest changes in performance specifications for the subsequent FSD phase, but in no case were those changes of importance to the overall mission or system design concepts.

Table 8

AAH PROTOTYPE PERFORMANCE SPECIFICATIONS

Performance (primary mission)	Specification
Hover out of ground effect	4000 ft at 95° F
Airspeed-cruise	145 kn
Lateral acceleration	.25/.35 g to 35 kn
Endurance	1.9 hr
Ordnance (disposable)	1300 lb

SOURCE: U.S. Senate, Committee on Armed Services, *FY1974 Authorizations for Military Procurement, Hearings*, 93d Cong., 1st Sess., Part 7, p. 4781.

Source Selection

One of the major uses of the prototype phase of each program studied was the selection among alternative approaches to the system design. The use of dual, competitive sources was established as a program design feature before any of the proposed designs were formally offered by the industry teams, so it seems unlikely that dual sources were justified on the basis of needing full scale test data to aid in the selection between competing design concepts. Whatever the justification for the dual sources, the system Project Office effectively used that feature to explore interesting design options in each program, and in some cases the prototype tests did reveal important differences in those design options.

AX. The prominent design differences between the two prototypes included the selection and placement of engines, a unique side force control system on the Northrop aircraft, and the use of a versatile auxiliary power unit on the YA-9. Fairchild opted for the higher-thrust TF34 because it believed that engine, adopted from an earlier Navy development program, represented a lower design and schedule risk than the lower-cost Lycoming engine, which was in a less advanced state of development. Both engines performed satisfactorily during testing. The aft placement of the engines in the Fairchild A-10 caused a serious problem because of inlet airflow distortion at high angles of attack, but subsequent design modifications alleviated the problem. The Northrop side force control proved less effective than had been expected and was deleted from consideration midway through the test program, but the APU turned out to be a highly desirable feature and was subsequently specified for inclusion in the A-10 design.

LWF. The YF-16 and YF-17 designs differed in several important respects: propulsion systems, cockpit design, flight control systems, and use of composite structure materials. The YF-16 used a single F100, an engine already developed for the F-15 program. By the time of the YF-16 first flight in early 1974, the F100 engine had already completed its model qualification test (MQT) and had accumulated over 2000 engine flight hours in the F-15 test program. Conversely, the YF-17 was designed around twin J101 engines, a model developed by General Electric largely as a private venture. When the YF-17 design contract was awarded early in 1972, the J101 engine had not even been run on a test stand in its final configuration, and it would be another seven years before the engine was fully qualified and ready for production. Thus, the YF-17 propulsion system represented a substantial risk area. Ironically, during the prototype flight test program the F100 engine caused more aircraft down time than did the J101.

A second important difference was the cockpit design. The YF-17 had a conventional two-piece canopy (forward part fixed) and a rather conventional seat that was tilted back 18° (rather than the approximately 15° in the F-15 and the F-4). The YF-16 used a one-piece "bubble" canopy and a seat that was tilted back 30°. The more radical YF-16 design proved quite effective, providing the pilot with better visibility and greater tolerance to high sustained "g" forces.

A third and probably the most important difference between the two designs was in the flight control system. The YF-17 control system was conventional, with standard stick and rudder controls in the cockpit and conventional mechanical linkages to the tail surfaces (pitch and yaw control). The ailerons were controlled by an electronic fly-by-wire system (no mechanical link between the pilot's control stick and the aileron surfaces). The control system on the YF-16 was decidedly unconventional. First, it was entirely fly-by-wire, with no mechanical linkages to any control surface. A quadruple-redundant analog computer controlled all aerodynamic surfaces by means of electrically powered servo motors. The second special feature of the YF-16 was a "relaxed static stability." The airplane was deliberately built to be slightly unstable at subsonic speeds and just barely stable at supersonic speeds, and the flight control system was given the job of making the airplane behave properly. The reduced level of inherent stability provides an enhanced response to control commands, thus improving the maneuverability of the vehicle. Another novel aspect of the YF-16 flight control system was the side-mounted "force stick," which was simply a handle mounted on the right-hand cockpit console with control signals generated by the pilot applying force to the stick. A control stick of this type had been flight tested in an experimental aircraft, but the YF-16 was the first application in a service-configured design. Experience showed that most pilots quickly adapt to the side force control stick and like it.

One final difference between the designs was that the YF-17 made greater use of composite materials in the structure. That had been a rather prominent "technology demonstration" goal in the program, but it turned out to be one of the less important advances in terms of final value to the weapon system capability. In fact, lessons learned during the prototype tests led to a reduction in the use of composite materials in the full scale F-16A program.

UTTAS. Because of the dominant emphasis on reliability and support cost, the few novel features introduced in the UTTAS designs were directed toward those goals. Sikorsky devised a transmission lubrication system using grease circulated under pressure, rather than oil, but it proved unsatisfactory early in the test program and was replaced by a more conventional system. A similar fate was suffered by a novel fluidic stability augmentation system that had few moving parts but that proved unacceptably sensitive to variations in temperature. Boeing Vertol developed a fiber composite material for the cabin floor, and it proved so successful that the Army directed its use in the winning Sikorsky design. Other design innovations tended to be of a detailed nature that affected component durability or repair characteristics.

AAH. Several design features were treated differently in the two competing configurations. One major difference was their contrasting placement of the pilot and his copilot-gunner. Contrary to their practice on earlier helicopters, Bell put their AAH pilot in front of the gunner, in the belief that for antitank work on the European battlefield, the gunner would be looking primarily into his sighting instruments (mainly the forward-looking infrared system plus the TOW's daylight visionics). Meanwhile, the pilot would need all the visibility he could get to execute nap-of-the-earth flight maneuvers. Hughes believed that the pilot could best perform his task by being as close to the aircraft's center of rotation as

possible, a location where he would be acutely sensitive to changes in pitch and attitude. Hence, Hughes located the pilot behind the gunner, just two feet from the main rotor shaft. Moreover, the pilot's seat was located 19 in. above the front seat, providing him with a good deal of visibility in any case.

Another layout difference that provoked some interest was the gun and sighting system placement. Bell located the 30-mm gun in its aircraft's nose and placed the FLIR and visionics equipment just behind and beneath it. Hughes reversed this order, placing the sighting equipment in a "chin-bubble," and the gun itself extended from a point beneath the gunner.

One result of the flight tests was that most of the conceptual differences separating the two designs were resolved in Hughes's favor. Locating the pilot near the aircraft's center of rotation proved beneficial, as did locating the 30-mm gun just beneath the gunner.

Source-Selection Summary. In each of the four programs studied, the competitive designs differed in some important ways, and the results of the prototype phase tests were useful in deciding which of the design concepts was preferred. Furthermore, the test outcomes sometimes were different from what was expected by the SPO personnel on the basis of the prototype design proposals. The demonstration of the effects of those design differences almost certainly played an important role in the source selection for the subsequent acquisition phases. However, in every case even the losing design would have been considered acceptable to the Service. Therefore, the introduction of a prototype phase may have resulted in a somewhat better configuration than would otherwise have been selected, but in this sample those differences appear small.

Hedge Against Uncertain Mission Needs

Only in the LWF program was the prototype phase used to hedge against uncertainties in the mission need for the system. The LWF prototype program was an outgrowth of the earlier Air Force F-15 program, which had involved a serious and protracted debate between advocates of a low-cost, simple day fighter and a larger, more expensive system that included a long-range, radar-directed air-to-air attack capability. When the F-15 program was underway and oriented toward the higher-capability, higher-cost end of the spectrum, advocates of the lower-cost, less-capable option utilized Deputy Secretary Packard's prototype program as a way of retaining some development momentum.[9] The LWF prototype program proved highly successful in this regard, with both designs eventually being selected for full scale development and procurement. It seems unlikely that either the F-16 or the F-18 programs would have emerged in their present form in the absence of the LWF prototype program, although such a conclusion must remain speculative.

Hedge Against Development Failure

Although each of the programs considered here used two competing contractors, there is little evidence that dual sources were justified as a hedge against the possibility that any one development program might run into serious technical problems. Thus it appears that, with the possible exception of the LWF program, hedging against technical uncertainty played little part in the programs considered in this study.

[9]The apparent discrepancy between this interpretation of the LWF program and its ostensible orientation as a "technology demonstrator" is discussed in Appendix B.

PROTOTYPE PHASE COSTS

The *direct* costs[10] of inserting a prototype phase in a weapon system acquisition program can be measured much more easily than can the benefits. We are concerned with both dollar cost and time.

Dollar Costs

The direct dollar costs of the prototype phase of each program is shown in Table 9, together with the total development cost (prototype phase plus FSD phase) and the current estimate of total acquisition cost.[11] The prototype phase for three of the systems cost from 15 to 25 percent of the total development cost, and in the UTTAS program the prototype phase consisted of nearly the entire FSD phase. In terms of the total acquisition cost the prototype consisted of only a few percent, again excepting the UTTAS program. A further breakdown of these costs is shown in the appendixes.

Table 9

COSTS OF PROTOTYPES
(Millions of 1981 $)

Item	AX	LWF	UTTAS	AAH
Prototype phase	176	199	672	301
Total development[a]	752	1357	758	1339
Total acquisition	5531	14724[b]	4414	4178
Prototype phase as %				
Of development	23	15	89	22
Of acquisition	3	1	15	7

SOURCE: September 1980 SARs. Base year costs converted to FY 1981 constant dollars using DoD deflators.

[a]Includes prototype costs.

[b]Covers only the USAF program of 1396 units.

An important question is whether the prototype phase costs are in addition to the costs that would have been incurred in a conventional full scale development program or are mostly recovered through savings in the subsequent FSD phase. To obtain some understanding of this question we estimated the cost of the *airframe* component of the two fixed-wing programs, using cost estimating relationships derived from conventional development approaches.[12]

The results are shown in Table 10. A range of values from the cost estimating relationships is shown, depending on the composition of the sample on which the model is based. In each case it can be seen that the actual cost of the FSD phase (after the prototype phase) was

[10]It is sometimes argued that a prototype phase also incurs indirect costs, such as vulnerability of the program to cancellation or substantial redirection. Those considerations are discussed in Sec. IV.

[11]In all cases, costs shown are costs to the government. Contractors almost certainly contributed some of their own money, especially in the prototype phases, but there is no reliable record of such expenditures.

[12]The method used is reported in H. E. Boren, *A Computer Model for Estimating Development and Production Costs of Aircraft*. The Rand Corporation, R-1854-PR, March 1976.

Table 10

AIRFRAME DEVELOPMENT COST COMPARISON
(Millions of 1974 $)

Item	AX/A-10	LWF/F-16
Cost estimating relationship (Conventional FSD program, one contractor)	180-250	250-270
Actual		
Prototype phase, two contractors	97	84
FSD phase, one contractor	180	231
Total	277	315

on the low side of the range of estimates for a conventional FSD program, suggesting that some savings had been achieved as a result of the prototype phase. However, the total development cost of the prototyped systems, including the cost of the dual prototypes, is greater than the range of estimates for a conventional development approach. If only one prototype model had been developed in each program, the costs would have been within, but on the high side of, the range of estimates for a conventional development approach. The cost of a development program using a competitive, dual-source prototype phase might be expected to be slightly higher than that of a single-source development program without a prototype phase, but any such cost difference is well within the uncertainty range of the parametric cost estimation procedures used here.

Development Time

One of the common arguments against the use of prototypes is that it delays the introduction of the new system into the operational force. This is an important consideration because any major delay in translating a particular level of technology into a fielded and fully operational system effectively reduces the combat value of that system.

To obtain some understanding of how a prototype phase affects total development time, we examined the history of Air Force and Navy fighter and attack aircraft that have been developed since 1950. The sample[13] included 11 models that were developed without a prototype phase and four models that included a prototype phase.[14] The results are displayed in Fig. 3. The FSD phase (ending in delivery of the first operational aircraft) following a prototype phase is considerably shorter, on average, than it is in those programs that omitted a prototype phase. The average length of the development phase for the 11 systems without prototypes was 51 months. For the four systems that started with a prototype, the average length of time from start of the prototype phase to delivery of the first operational aircraft

[13]Data drawn from G. K. Smith and E. T. Friedmann, *An Analysis of Weapon System Acquisition Intervals, Past and Present*, The Rand Corporation, R-2605-DR&E/AF, November 1980.

[14]The A-7 was excluded because it was a derivative of the F8U and the F-18 was excluded because a substantial period of time elapsed between the prototype YF-17 development and the Navy decision to adapt the design for service use.

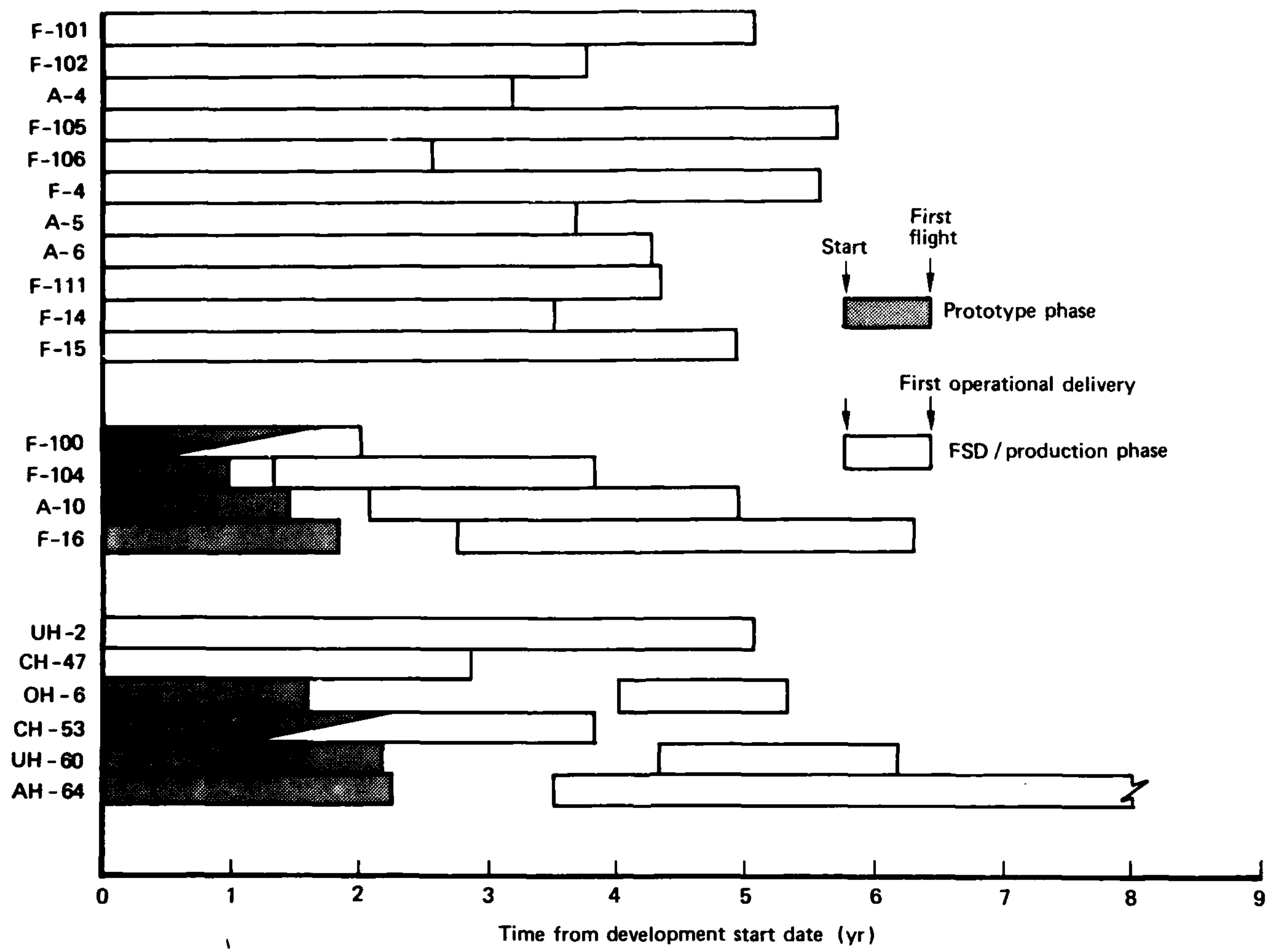


Fig. 3—Comparison of development times

was also 51 months. Although this is a rather small sample, it strongly suggests that the inclusion of a prototype phase does not usually extend the total development time.

The above comparison assumes that the decision to start a prototype phase is equivalent to that of starting a full scale development phase. That is not always the case, because initiating a prototype phase sometimes implies no commitment past that phase, and start of full scale development almost always implies a strong commitment to complete the development and put the system into production. Therefore, if we assume that a prototype phase is sometimes initiated earlier than the same system could have been approved for a conventional full scale development (as was surely the case with the F-16, for example), then that might actually lead to earlier introduction of a fielded system than would otherwise be the case.

A similar comparison was attempted for helicopters, but the readily available data were not sufficient to establish a significant sample. Results are included in Fig. 3 and, with the exception of the AH-64 (which was delayed because a new missile system was introduced at the end of the prototype phase), the effect of introducing a prototype phase in helicopter development appears roughly comparable to the effect in fixed-wing airplanes.

Of course, any comparison of fielding date (IOC, first operational delivery, etc.) is complicated by the fact that truly effective operational capability is sometimes delayed several years because of problems in system performance and reliability. If, as discussed above, a prototype phase can lead to a system with fewer such problems when production starts, that effect could add another important saving in total effective acquisition time. Unfortunately, we have no practical way to measure the "effective" operational date, so this potential benefit of prototyping cannot be quantitatively analyzed.

Cost and Schedule Summary

Some very limited evidence suggests that the introduction of a prototype phase might increase the total development cost of a system, especially if dual competitive sources are used in the prototype phase. However, a prototype has little, if any, effect on the total time required to bring a system to operational status. Indeed, if the prototype phase is initiated "on speculation," before achieving the consensus needed to start full scale development, the system might actually be fielded at an earlier date than otherwise would have been possible.

PROGRAM MANAGEMENT CONSIDERATIONS

The Army and the Air Force used radically different management styles in their prototype programs. The Air Force applied some innovative practices in the prototype phases of the AX and LWF programs, including:

1. *Sparse definition of product.* Contractors were provided with system performance goals and with indications of where additional capability would be desirable, but no particular levels of performance were mandated. Furthermore, very few process specifications were imposed, thereby relieving both the contractor and the Project Office of the task of verifying compliance. The contractor was charged with delivering his "best effort" without having to meet any other contractually mandated product description. Because of this arrangement, the contractor had considerable freedom to make his own decisions among design alternatives, although in practice he frequently sought the informal consensus of the Project Office.

2. *Strict funding limits.* In return for the flexibility in the product specification, the Air Force imposed rigid funding limits on the contractors during the prototype phase. In the AX program a firm fixed price contract was used. The LWF program employed a cost-plus-incentive-fee contract but a limitation-of-government-obligation clause was added that turned it into a fixed price contract. In both programs the cost to the government was exactly that of the original contract.
3. *Lean management, sparse documentation.* The management structure at both the contractor and Program Office was remarkably lean. Program Office staff consisted of a few tens of people, and the entire contractor work force (management and design team) was never more than a few hundred people. Documentation was limited to what was essential for the contractor to perform the design task, and reporting chains were very short. Direct verbal communication and action approval between the staff person and the manager was the norm.
4. *No production commitment.* During the prototype phase there was no commitment to a follow-on production phase. This permitted everyone involved in the program to concentrate on refining the design and bring it to a satisfactory level without having to worry about the consequences of any changes on a subsequent production design. Although modest resources were devoted to production aspects during the prototype phase, the basic designs were drawn with the expectation that they would eventually be produced in quantity.
5. *Use of competition.* The competitive structure of the program substituted in many ways for the lack of conventional management controls by the Program Office. During the competitive prototype phase the contractors efficiently corrected deficiencies in their designs without Program Office intervention. One problem introduced by the competitive posture was that the Program Office was sometimes inhibited in suggesting changes in one design because such comments might convey proprietary information or unfairly enhance the competitive edge of one firm. Conversely, the existence of competition almost certainly inhibited both the contractors and the SPO from making any unnecessary changes, thus providing an unusually stable design environment.

It is not possible to make a quantitative evaluation of the effect of these management innovations. However, the prototype phases of both programs were widely judged to have been technically quite successful, and all participants in the programs considered the management structure to have been a significant factor in that success.

Conversely, the prototype phases of the two helicopter development programs reviewed in this study were structured and managed in much the same way that they probably would have been in a conventional full scale development program. The Army first conducted extensive studies to determine the performance levels obtainable for a given level of risk and then issued RFPs that specified the desired system in great detail. CPIF contracts were used for the prototype phase, and the Army Project Office used the usual management practices to control the expenditures of the contractors. Although competition probably inspired the contractors to provide their very best effort, the Army does not seem to have used it as a substitute for close supervision of the contractors, at least not to the extent observed in the Air Force programs.

IV. CONCLUSIONS AND RECOMMENDATIONS

In the ideal analysis we would compare the outcomes of many prototype programs with the outcomes of many programs that did not have a prototype phase and measure the differences in outcomes against the costs of the prototype phase. Unfortunately, the small sample size prevents such an approach, and we must infer some cost/benefit comparisons from fragmentary evidence.

COSTS AND BENEFITS

Costs are somewhat more easily identified than benefits. The absolute costs will vary over a large range depending on the kind of system being developed and on how much of the complete system is included in the prototype phase. It is more useful to examine the prototype phase costs as a fraction of total acquisition costs. Our sample indicates that an austere prototype phase of a large program can cost as little as 1 percent of the total acquisition cost, even if dual competitive sources are used. If, as in the UTTAS program, the issue to be resolved requires that nearly the complete system be prototyped and tested, and the expected procurement quantities are modest, costs can approach 10 percent of total acquisition per source. The actual net cost of the prototype phase is probably somewhat less than the apparent direct cost because of subsequent savings in the FSD, production, and operations phases. Furthermore, the apparent cost of the prototype should be adjusted to reflect any true reduction in subsequent acquisition cost growth that can be traced to any influence of the prototype phase. There is some evidence that on average, cost growth of prototyped programs is less than that of conventional acquisition programs, and such savings exceed the direct cost of the prototype phase. However, the cause and effect relationship must remain speculative, and limited attempts to quantify such savings have been unsuccessful. Furthermore, such "savings" may simply be a reflection of more accurate (higher) initial estimates of cost and therefore should not be equated to any reduction in real cost.

The *time* required to develop a new system is another important resource that must be considered in the selection of a development strategy. Many have claimed that a prototype phase lengthens the total acquisition time. However, the histories of attack and fighter aircraft developed by the Navy and the Air Force since 1950 indicate that introduction of a prototype phase makes little difference in total development time. Furthermore, if a prototype program can be started earlier than an equivalent full scale development program (as was certainly the case with the LWF program), then a prototype phase may lead to an *earlier* fielding date.

Of course any comparison of fielding date (IOC, first operational delivery, etc.) is complicated by the fact that truly effective operational capability is sometimes delayed several years because of problems in system performance and reliability. If, as seems likely, a prototype phase can lead to a system with fewer such problems when production starts (see below), that effect could add another important saving in total effective acquisition time. Unfortunately, we have no practical way to measure the "effective" operational date, so this potential benefit of prototyping cannot be quantitatively analyzed.

Efficiency

In each of the four programs, the prototype phase contributed to the process of identifying and correcting design flaws, but the efficiency (and thus the benefit) of that process varied substantially. In the two Air Force projects the prototype test program yielded numerous fixes to design problems, few new changes were introduced during the transition to FSD, and the prototype phase costs were small. Thus the prototype phase provided an opportunity to identify and correct numerous design deficiencies more quickly and cheaply than would have been the case in a conventional full scale development program. This claim is supported by the relatively trouble free experience of those designs during subsequent phases of development. Design problems were also identified and corrected in the prototype phase of the helicopter programs, but there the engineering work conducted on the prototypes was nearly equivalent to that of a normal full scale development, so there was less opportunity for achieving an appreciable gain in efficiency except through direct competition. Furthermore, in the AAH program a major design change was made after the prototype program was completed, almost certainly negating some of the maturation work completed at that point.

Competition

All four of the systems reviewed in this study used two competitive sources throughout the prototype phase. Lacking noncompetitive "control" programs, we must rely on subjective interpretations of the consequences of the competition. Those interpretations differed somewhat between the Army and Air Force program managers, in part because the services designed the prototype phase of their programs differently. In the two Air Force programs the system program manager had a very small staff during the prototype phase, relying instead on the competitive environment to ensure that the contractors performed effectively. The Air Force managers believed that the arrangement was highly successful. Conversely, the Army prototype programs used detailed contracts and extensive Program Office staffs, and opportunities were reduced for exploiting the competitive environment as a substitute for Project Office management controls over the contractors.

Nearly everyone agreed, however, that the contractors were more responsive to Program Office direction while in a competitive environment than they were after entering into the sole-source phase of the program. This effect cannot be measured in any practical way, but it is still an important potential benefit. Many experienced managers believe that the efficiencies resulting from a competitive environment during a part of the development phase could exceed the direct costs involved, and that view does not appear unreasonable.

Quality of Decisions

There is little evidence that the quality of cost and performance data available at the end of the prototype phase led to program decisions or predictions substantially better than those of typical programs lacking a prototype phase. Each prototyped program has experienced some cost growth since the start of full scale development, although on the average the growth rate has so far been somewhat less than that of other programs. Each of the prototypes demonstrated most of the desired performance goals, but only the LWF was characterized as having performance goals that were very challenging. The fact that in each program both competitive sources produced a model that had "acceptable" performance is a further

indication that none of the four programs involved exceptional technical risks. It seems inappropriate, therefore, to credit the prototype phase with large reductions in decision risk regarding system performance predictions. That conclusion is clearly limited to systems that do not involve high-risk design features. For example, a VTOL airplane involves aerodynamic and propulsion characteristics that are very complex and difficult to predict with current analysis methods, and a prototype phase would be almost mandatory for such systems in order to demonstrate and validate performance predictions.[1]

Each of the four programs involved dual, competitive sources during the prototype phase, and prototype test results undoubtedly contributed to the selection of the single source for subsequent development and production phases. Furthermore, there is anecdotal evidence that in some cases the test results led to selection of a source different from the one that probably would have been selected on the basis of "paper" design proposals. Thus the prototype phase seems to have improved the quality of some source selection decisions and almost certainly improved the confidence of the decisionmakers. However, in these cases the second best would probably have been nearly as good, so the value of this benefit is difficult to assess.

Hedge Against Uncertainties

Only the LWF program provides a reasonably sharp indication of the effect of conducting a prototype phase. That program was designed mostly as a hedge against the possible need for a system quite different from the ones then being developed and procured for the tactical air forces. By the time the prototypes had entered flight test, it was decided that such a system was needed, and the program quickly transitioned into full scale development. Thus the prototype phase served two identifiable functions:

1. It provided a tangible option, which served as a catalyst for the full system-level decision. It seems unlikely that anything resembling the multi-national F-16 program would have emerged without the existence of the Lightweight Fighter prototype program.
2. It permitted an earlier operational capability. If a conventional full scale development program, without a preceding prototype phase, had been authorized in mid-1974, that program probably would have taken one to two years longer than did the actual FSD phase of the F-16, which benefited from the preceding prototype phase.

Our conclusion is that in the LWF program we can confidently identify some ways in which a prototype phase had important effects on program outcomes, but in the other three programs the prototype phase effects were smaller or subject to considerable uncertainty. In the AX, AAH, and UTTAS programs the prototypes did not provide a hedge function, nor did they resolve any critical issues on which the future of the program depended. That is, the prototypes did not affect any major program decision except source selection, and in those three cases source selection does not seem to have been a pivotal issue. There is some evidence that all four programs benefited from the application of competition and that two of the programs achieved some development efficiency through early, low-cost detection of design flaws, but those effects are impossible to measure in any confident way. Our inability to

[1]A good example is the AV-8 Harrier, the only successful VTOL aircraft now operational in the U.S. Forces. That system went through three distinct development phases before reaching operational status. See J. R. Nelson and J. R. Gebman, *Future V/STOL Airplanes: Guidelines and Techniques for Acquisition Program Analysis and Evaluation—Executive Summary*, The Rand Corporation, R-2397-PA&E, February 1980.

measure such benefits should not be interpreted as indicating their lack of importance; the sample size is too small to permit more confident conclusions.

PROGRAM ORGANIZATION AND MANAGEMENT

There is no widely accepted doctrine on how to organize or manage a prototype program, nor is there even a well developed body of literature on the subject. Even the small sample of four programs reviewed in this study involved many management organizations and styles, dictated in part by the different objectives sought in those programs. Nevertheless, even this varied set of experience supports three conclusions.

If development efficiency is a major objective of the program, a flexible contracting and management structure is necessary. Efficiency is most probable if many design flaws are detected early and at low cost and if the designers then have the freedom and incentive to quickly devise and test solutions to those problems. The two Air Force programs studied here achieved those goals substantially by using competition to provide incentive and by not contractually obligating the industry teams to achieve any specified set of performance capabilities or to follow any particular design practices or procedures. That arrangement gave the industry teams an opportunity to concentrate their attention initially on the risky and innovative parts of the design concept and later to modify the designs in what seemed the best way to achieve a broad set of performance goals, all without involving any lengthy contractual negotiations. This kind of flexible contracting and management structure is very different from that applied to most weapon system development programs conducted during the past couple of decades.

One of the major decisions in the design of a prototype program is whether to use multiple, competitive sources. All four of the programs studied here had dual sources, and interviews with Service Program Office personnel indicate a strong belief that the competition stimulated the industry teams to work at higher levels of dedication and efficiency than would otherwise have been likely. In the Air Force programs, competition substituted for some system program office management overview. In those cases, the contractors were given great freedom in responding to a broadly worded system specification, and the managers generally believed that the cost of a second source was well justified by the additional stimulation provided to the system designers. In the two Army programs, with somewhat different objectives and management organizations in the prototype phase, it is more difficult to conclude that the costs of the second source were justified by the results. The desirability of a second competitive source in the prototype phase depends on the characteristics and objectives of the particular program and must be assessed individually in each case.

Finally, to obtain maximum benefit from the prototype, the full system operations concept should be well thought out before the prototype phase is begun. There are two reasons for this admonition. First, many decisions made during the design process, even at the prototype level, depend on how one expects the eventual weapon system to be operated. In the LWF program, which lacked a well developed operational concept at that stage of its development, designers and program managers had to use their own judgment in many design questions that depended on how the system would be operated.[2] A second, and possibly more important, reason for having a total system operations concept is that it is not otherwise

[2] Lack of an operational concept for the LWF stemmed from the fact that the program was not *formally* designed as a potential operational system. That does not diminish the value of the lesson observed here.

possible to assess the objectives of the prototype phase accurately or to ensure that the correct elements of the system are included. The design concept developed in the prototype phase should be the one taken into full scale development. Any significant changes in design concept or performance specification introduced after the prototype phase (except those dictated by prototype test results) will probably diminish the benefits of that phase.

WHEN SHOULD PROTOTYPES BE USED?

Despite the lack of quantitative comparisons between programs with and without prototypes, we can infer some general guidelines on prototypes by reviewing the list of potential benefits.

If the new system involves much technical risk, and almost every new weapon system will, a prototype phase can be designed to improve the efficiency of finding and correcting many of the inevitable design flaws. A prototype program that includes the initial development and test of the most critical system components, together with a contractual and management strategy that permits rapid and flexible response to technical problems, can almost surely resolve many of those problems at a fairly small investment of time or money. Conversely, if those same flaws emerge only at the end of full scale development, where major investments have already been made in production facilities and all the complex infrastructure needed to produce and operate a new system, their correction is much more difficult and expensive. This approach also provides the opportunity to use prototype phase results to improve confidence in estimates of future program outcomes.

Another use of prototypes that appears promising in today's environment is to use an austere prototype as a way of hedging against uncertainty in future operational needs. Such uncertainty always exists, and in any major mission area there are usually two or more different design concepts advocated as solutions to future needs. If a prototype of one or more such candidate solutions can be started early in the decision process, an important option may have been created or preserved. If, sometime later, one of the designs that had been prototyped is deemed responsive to an operational need and the decision is made to complete the development, then the experience gained in the prototype phase can lead to a faster and lower-cost development completion, and the decisionmaker can have somewhat higher confidence in the predicted program outcomes. In the best circumstances, when two or more designs are prototyped and one is then selected for further development with little change in specification, it may be possible to achieve most of the potential benefits we have identified: efficiencies during development, increased confidence in predictions of future program outcomes, and a hedge against uncertainty in mission needs.

The conditions under which these benefits may be considered sufficient to justify the associated cost of a prototype phase is highly situation dependent, but managers should be able to appraise their own program and decide if a prototype phase would be appropriate.

RECOMMENDATIONS

Prototyping should be treated as one of several standard and acceptable development options. During the concept formulation of every new weapon system, the project manager should review the possible benefits of using a prototype phase. Acquisition policies and procedures should encourage a prototype phase early in the evolution of a new weapon system, so

that critical hardware development could proceed at modest cost while the need for a full system development and production program was still being debated.

Management of a prototype phase is frequently very different from management of a full scale development program. Prototype management experience should be systematically accumulated so that each manager faced with organizing and conducting a prototype program could draw on the experience of previous programs.

Appendix A

THE AX PROTOTYPE PROGRAM[1]

The acquisition history of the Air Force's A-10 Close-Air-Support attack aircraft can be traced to about 1966, when the Air Force began to formulate its concept for a fixed-wing aircraft that could

- Deliver ordnance accurately near friendly troops.
- Be highly maneuverable.
- Operate at low speeds under low-ceiling and low-visibility conditions.
- Survive the probable enemy defenses.

Deciding that no airplane in the existing inventory or under development could satisfy these characteristics, the Air Force awarded CAS design study contracts for the AX in May 1967 to General Dynamics/Convair, Grumman, McDonnell Douglas, and Northrop. The Air Force wanted the contractors to develop an information base it could subsequently use to specify the desired performance characteristics for an operational system.

The contractors were directed to follow three design principles: (1) minimize total system cost, (2) minimize aircraft attrition, and (3) maximize target destruction. Setting a unit flyaway cost goal of about $1 million for 1000 aircraft, the Air Force encouraged the contractors to use current technology in the design of simple planes having limited avionics and low operation and maintenance costs.

The contractor studies resulted in one single-engine turboprop tractor design, one geared twin-turboprop driving a single pusher propeller, and two twin-turboprop tractor designs with engines mounted on the wings. All used a proposed 30-mm Gatling gun as primary armament. Cost estimates for the aircraft generally fell within the guidelines established by the Air Force.

EVOLUTION OF THE ACQUISITION STRATEGY

The Air Force drew on the contractor design studies to put together a Concept Formulation Package in the spring of 1968 "to justify conditional approval for Contract Definition and Engineering/Operational Systems Development for a new *specialized* Close Air Support Aircraft (A-X)." The Air Force clearly intended to develop the AX in the conventional manner, but it could not persuade the Office of the Secretary of Defense to approve funds to begin the program. However, in October 1968 the Senate Judiciary Committee's Subcommittee on Anti-trust and Monopoly requested that the GAO evaluate two "possible means for enhancing competition in the procurement of weapon systems, components, spare parts, and other defense items"—Directed Technical Licensing and Parallel Undocumented Development (competitive prototyping). In its July 1969 report to Congress, the GAO recommended competitive prototyping, coupled with austere management and limited documentation, to prevent excessive cost overruns in weapon system acquisitions. The GAO recommended that

[1]Teresa Barrett assisted in the preparation of this case study.

three major weapon systems be considered for competitive prototyping, including the AX.[2] The OSD concurred with GAO's choice of the AX, and in 1970, Defense Secretary Laird's posture statement indicated that the aircraft would be developed using a competitive prototyping strategy.[3]

Once the prototyping path had been chosen, the Air Force reworked the AX concept formulation package to include its latest technical and operational specifications and to incorporate the competitive prototyping decision. The Air Force Systems Command issued a brief and direct RFP on May 7, 1970.

In addition to specifying performance requirements to be achieved on a best-effort basis, the RFP set a "cost goal . . . of *less than $1.4 million* per unit flyaway (recurring costs in FY 70 dollars) for a 600 aircraft buy at a peak-production rate of 20 aircraft per month."[4] Thus, along with its other distinctions, the AX became one of the first major weapon system developments governed by design-to-cost principles. Although the DTC goals were confining, and the RFP committed the Air Force only to a prototype phase, the incentive of a probable downstream buy of at least 600 aircraft did induce responses from six of the 12 companies invited to bid.[5] In December 1970, Air Force Secretary Robert C. Seamans, Jr., announced that the winners of the AX prototype development contracts were the Aircraft Division of the Northrop Corporation and the Republic Aviation Division of the Fairchild Hiller Corporation. Northrop had bid $28.8 million for the program, and Fairchild $41.1 million.

DEVELOPING AND FLIGHT TESTING THE PROTOTYPES

The Air Force award of contracts to Fairchild and Northrop in December 1970 signaled the beginning of a scheduled 26-month competitive prototype phase. This included the development, construction, and test flight of two prototypes by each contractor and culminated in the award of a full scale development contract to Fairchild. The Air Force then used the winning prototypes for more than two years of performance validation and operational testing before development test and evaluation (DT&E) aircraft became available. The major program milestones are shown in Fig. A.1.

Program Management During Competitive Prototype Phase

Because of the severe competition for defense dollars from its higher priority programs such as the F-15 and B-1, the Air Force seemingly had little choice but to adopt an austere development approach for its close-support aircraft. Both the Air Force and its two prime contractors were austere in spending money and using personnel during the CPP. Figure A.2 shows that the approach initially featured an extremely small System Project Office (SPO) consisting of approximately 30 persons, about half of them engineering personnel; but it also included representatives of the Air Force Logistics Command and the Tactical Air Command. Approximately a year and a half into the program, staffing had grown to 80, still considerably less than the 1977 level of 200 to 250. Although the minimal manning level demanded

[2]The other systems the GAO recommended were the F-15 fighter aircraft and the Subsonic Cruise Armed Decoy (SCAD). See U.S. GAO, *Evaluation of Two Proposed Methods* . . ., B-39995, July 14, 1969, pp. 19-31.

[3]U.S. House of Representatives, *Military Posture, FY 1971*, March 3, 1970, pp. 6892-6893.

[4]Emphasis in the original RFP.

[5]Boeing's Vertol Division, Cessna Aircraft Company, Fairchild Hiller's Republic Aircraft Company, General Dynamic's Convair Division, Lockheed Aircraft Corporation, and the Northrop Corporation responded to the RFP.

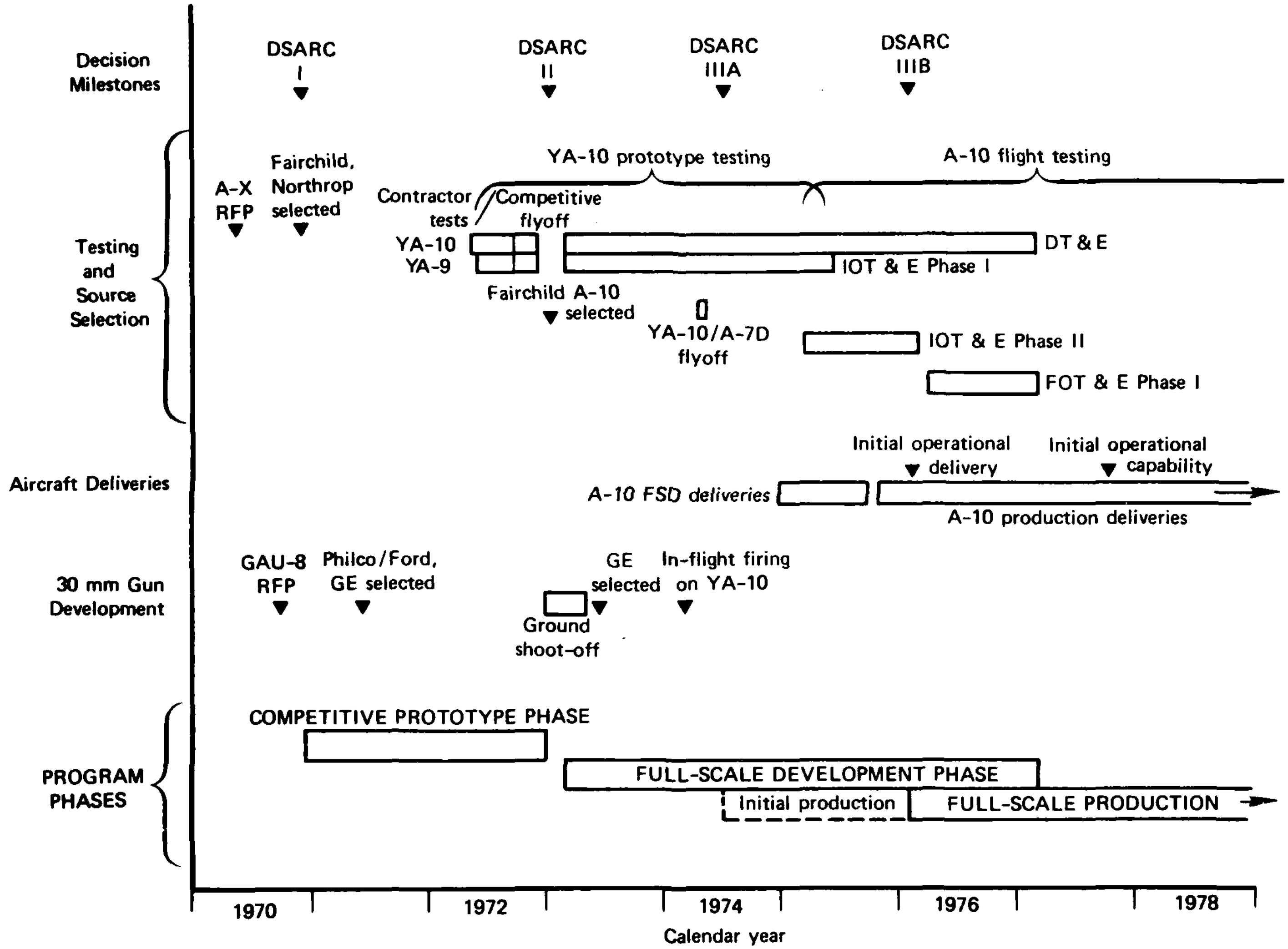


Fig. A.1—AX/A-10 program schedule

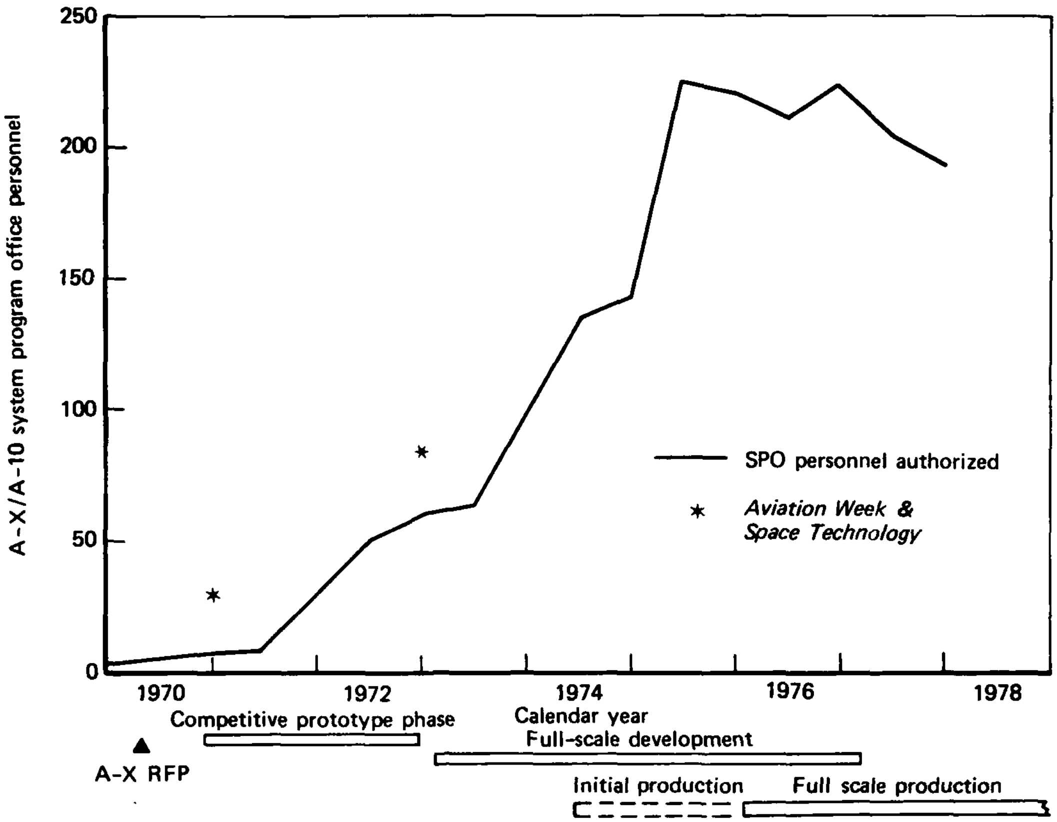


Fig. A.2—AX/A-10 SPO manning history

that many SPO personnel perform multiple functions, most program participants seemed satisfied that few, if any, important oversights occurred.

AX SPO Director Colonel James E. Hildebrandt operated under two important advantages: constant program requirements and considerable operational autonomy. The unchanged set of requirements throughout the competitive prototyping phase distinguishes the AX program from the lightweight fighter program, which began as a technology demonstration program and evolved into a multinational fighter development. Without the burden of new or changing requirements, both the SPO and the contractors generally met the originally established objectives on schedule and within budgeted costs. Col. Hildebrandt kept his superiors informed through quarterly progress report briefings to the USAF Air Council, the Secretary and assistant secretaries, and the Chief of Staff, after review by ASD and AFSC commanders.

The Competitive Prototype Phase RFP set the tone for the flexible management approach:

> The [Air Force] management relationship with the contractors ... will be one of minimal involvement increasing at the test-flying stage to one of appropriate Air Force participation. The Air Force involvement ... will be limited to "overview visibility" consisting of monthly visits to the contractors by selected SPO personnel. ... Air Force approval, surveillance, control or directive actions will be minimal unless ... the objectives of the requirements documents will not be met and Government participation is required.

The SPO kept abreast of the contractors' progress through personal and informal communications with the contractors during the construction phase, rather than relying on large quantities of documentation.[6] Contractor reaction to this approach was favorable, but using the austere management and reporting philosophy does not necessarily guarantee success. Because of the small number of people involved, the personalities and capabilities of particular individuals can critically affect the success of the project. This perhaps places a greater burden on the Air Force in staffing the SPO with the appropriate personnel than might be the case with a more formalized program structure.

There were few formal documentation or reporting requirements to fall back on if the informal management approach had not succeeded. The CPP RFP specified:

> It is intended that formal data requirements will be held to an absolute minimum during [the] Competitive Prototype Phase.
>
> The contractor will prepare and maintain a data file to assure good communications with the AX SPO. The data should be minimal and essential. The data shall be in contractor format and provided to the SPO upon request.

Embracing this concept with enthusiasm, the contractors still generated and used data on aircraft systems and subsystems but avoided the time, work, and expense of assembling the material into formal documents for the Air Force.[7] For example, Northrop's minimal documentation to the SPO consisted of updated monthly status reports and a brief technical narrative every two months.[8] Additionally, although contractors did not integrate data into formal external documents, SPO engineers did have easy access to contractor working documents and design specifications.

Working with firm fixed-price contracts, Fairchild and Northrop employed similar management approaches. Each featured (1) project-like organizations, (2) controlled access facilities physically separated from other plant activities, (3) program managers with full responsibility and direct authority over the programs, (4) short reporting chains, and (5) austere manning.

Both program managers had full responsibility and direct authority for their programs, including responsibility for cost control. The Fairchild manager reported directly to the Vice President and General Manager of his division, only one office removed from the office of the corporation president. The Northrop manager initially reported to the Vice President for Engineering, but later he also began reporting to the Vice President and General Manager of his division. In principle, at least, the contractors also had short reporting chains in the opposite direction. For example, only two tiers of management separated the Northrop program manager from the board engineer or working mechanic.

---

[6] "A-X Fighter Paved Way ...," *Aviation Week & Space Technology*, June 26, 1972, p. 103.
[7] "A-X Fighter Paved Way ...," *Aviation Week & Space Technology*, June 26, 1972, p. 117.
[8] "Northrop Streamlines A-9A Management," *Aviation Week & Space Technology*, June 26, 1972, pp. 107-108.

The contractors claim the aforementioned approach, together with other factors, permitted them to use substantially less manpower than might otherwise have been expended in a typical program. Fairchild indicated this approach permitted it to reduce by about 80 percent the manhours normally required to reach first flight, and Northrop indicated roughly 70 percent. Both contractors designed, constructed, and flew their prototypes ahead of schedule using personnel numbering in the hundreds rather than the thousands.[9]

Designing the Prototypes

The contracts signed by the two companies did not commit the Air Force to any subsequent development or production after the prototyping phase. Even so, the wording and structure of the RFP left little doubt that the Air Force ultimately intended to develop a production version of the AX for the inventory if the results of the prototyping phase indicated a production airplane could meet cost and performance requirements. The prototype phase RFP stated that "The A-X is intended to be the Air Force Specialized-Close-Air-Support aircraft for employment by the Tactical Air Command in the 1975-1985 time period." The actions of the contractors seemed to indicate their confidence in the Air Force's intentions as well, since they both reportedly devoted considerable attention to production planning, including extensive tradeoff studies aimed at enhancing the producibility of the aircraft at low cost.[10]

The Competitive Prototyping Phase RFP gave the contractors considerable freedom in the design of the prototypes, while still apprising them of what requirements to anticipate for a production aircraft. For example, the RFP required that the production aircraft have a self-contained and self-sufficient starting capability, whereas AGE could be used for the prototype. The production aircraft had to have the capability of operation from semiprepared forward airstrips, whereas the prototype could use existing landing gear limited to operations from paved runways. Although the production aircraft would have as its primary armament the 30-mm gun system then under development, the prototypes used a 20-mm M-61 cannon, although they had to have space and weight provisions for the larger gun.[11] The RFP required that only the production aircraft have an aerial refueling capability and left selection of the propulsion subsystem to the contractors, specifying only that the AX use two turbine engines.

---

[9]In contrast, in the F-111A program, admittedly a much more complex system, project manning reached 4000 to 6000. Robert L. Perry et al., *System Acquisition Strategies*, R-733-PR/ARPA, June 1971.

According to Northrop proposal documentation, total manpower was predicted to peak at slightly more than 600 persons, technical and logistics manpower around 220, and production manpower around 420. Other sources suggest engineering and manufacturing manpower never exceeded much more than 300 persons. "A-X Fighter Paved Way . . .," *Aviation Week & Space Technology*, June 26, 1972, p. 107.

Fairchild proposal documentation predicted its manpower would peak at slightly over 800 persons, engineering manpower around 300, and manufacturing tooling manpower slightly less than 500.

[10]See, for example, Peter W. Odgers, *Design-to-Cost . . .*, Air War College, Report No. 5370, April 1974; also "Northrop Streamlines A-9A M nagement," and Hansen Woods, "A-10 Prototype Designed for Production," *Aviation Week & Space Technology*, June 26, 1972, pp. 107-118.

[11]Controversy about the tank-killing ability of a 30-mm gun, emphasis on the 25-mm gun under development for the F-X (F-15), and a variety of other reasons delayed GAU-8 gun development relative to the AX aircraft development. A select panel of the Air Force Scientific Advisory Board assessed the risks associated with GAU-8 gun integration in the YA-9 and YA-10 and recommended the Air Force not delay the AX prototype competition and source selection for the availability of the 30-mm gun.

Development of the GAU-8 began in June 1971 with the award of competitive prototype development contracts to General Electric and Philco Ford. The gun development program formally became a part of the AX program in September 1971. After a competitive ground shootoff, the Air Force awarded General Electric a full scale development contract in June 1973. The first in-flight firing of the gun in the YA-10 occurred in February 1974, 21 months after the first YA-10 flight.

In general, the RFP gave the contractors considerable freedom in subsystem design and made very few demands for subsystem testing.

The RFP formally constrained the contractors to meet only nine military specifications, primarily in those areas directly affecting flight safety and aircraft handling qualities.[12] The entire engineering requirements attachment to the RFP consisted of only 20 pages. The RFP specified airplane performance *requirements*, but also stated on the very first page, "These system requirements are to be achieved in the prototype aircraft on a best-effort basis by the contractors." Although the terminology "requirement" was used throughout the RFP, this qualifier made the performance requirements flexible *goals* that the Air Force wanted the contractors to strive to achieve. The RFP explicitly stated the $1.4 million per unit flyaway cost (FY 70 dollars, 600-aircraft buy, peak production of 20 aircraft per month) as a goal. It distinguished between system characteristics in which "more was better" (e.g., the best possible sustained "g" capability within rational cost constraints) and those in which "more was not necessarily better" (e.g., a much shorter takeoff distance than required was not necessarily of great value). Terming those system characteristics falling in the former category as stimulative items and those falling in the latter category as threshold items, the RFP gave the contractors guidance about what performance characteristics the Air Force deemed most important.

The performance requirements, Table A.1, called for a subsonic aircraft capable of carrying large payloads, having long range/endurance capabilities, good low-altitude maneuverability, and short field takeoff and landing capabilities from forward airstrips (production aircraft only). The RFP also made important demands relating to aircraft survivability and flying qualities for weapon delivery. It required a fully redundant flight-control system with a manual backup to enhance survivability. It also required immunity from single direct hits from most antiaircraft devices, although this was not tested on the prototype flight articles themselves. Since the RFP specified that the AX prototype and production aircraft have only the minimal essential avionics, including a manual bomb delivery system, the RFP emphasized the desirability of having excellent flying qualities for accurate manual weapon delivery. Underlying all these requirements was the need to design the aircraft so that it could eventually accommodate its primary weapon, the 30-mm gun system, and cost no more than $1.4 million per unit.

Fairchild's prototype design featured a single-place, low-wing, low-twin-tail configuration with two General Electric YTF34/F5 General Electric turbofan engines installed in nacelles mounted on pylons extending from the fuselage just aft of and above the wing. Northrop's high-wing design had integrated wing root inlets, a conventional empennage, and two AVCO Lycoming YF102-LD-100 turbofans. Although there were design differences between the prototypes, as Table A.2 indicates, the aircraft shared many characteristics.

Four of the more prominent design differences that did exist between the two prototypes included the selection and placement of engines, a unique side force control system on the Northrop aircraft, the use of a versatile auxiliary power unit (APU) on the YA-9, and the design and placement of the main landing gear. Fairchild opted for the higher-thrust TF34 because it believed that engine represented a lower design and schedule risk than the Lycoming engine. The YTF34/F5 was a modest adaption of the TF34-GE-2, which had been under

[12]Military specifications or standards included (1) definitions of minimum permissible speeds, (2) flying qualities requirements, (3) criteria for noise in the crew station, (4) white lighting requirements for the crew station, (5) requirements for instruments and plastic plate control panels, (6) certification of the crew egress system, (7) safety design guidance, (8) definitions of standard tropical day atmospheric environment, and (9) mission rules for computing fuel allowances for ground-support fighters.

Table A.1

PERFORMANCE REQUIREMENTS FOR THE AX

Parameter	Requirements/Goals
Speed	
Maximum level flight speed at 5000 ft, BMFDW[a]	350 kn
Maximum level flight speed, clean at sea level[b]	400 kn
Maximum design speed (all configurations)[b]	450 kn
Cruise speed at 5000 ft, BMFDW[b]	300 kn
Maneuverability[a]	
Sustained load factor - 150 kn	2.2 g
(at 5000 ft at BMFDW) - 275 kn	3.5 g
Instantaneous load factor - 150 kn	2.2 g
(at 5000 ft at BMFDW) - 300 kn	5.0 g
Airport performance[a]	
Takeoff ground roll	
at maximum takeoff weight	4000 ft
at forward airstrip weight	1000 ft
Landing ground roll	
at maximum takeoff weight	4000 ft
at forward airstrip weight	1000 ft
Mission performance	
Close air support radius/loiter (18 Mk-82s)[c]	250 n mi/2.0 hr
Armed reconnaissance radius (18 Mk-82s)[a]	350 n mi
Ferry range (50 kn headwind)[a]	2300 n mi
Payload	
Maximum payload (partial fuel)[b]	16000 lb
Maximum payload (full internal fuel)[d]	~12000 lb

BMFDW--Basic mission flight design weight; 6 MK-82 500-lb bombs, 750 rounds 30-mm ammo.

Forward airstrip weight includes 4 Mk-82s, 750 rounds, 50 n mi cruise to combat, 150 n mi cruise home.

Performance stated for tropical day conditions.

No ferry requirement for prototype.

Prototype required to operate from paved runways only.

[a] J. Philip Geddes, "A-10--USAF Choice ...," *Int. Def. Rev.*, Jan. 1974, pp. 72, 74.

[b] U.S. Senate, *Fiscal Year 1972* ..., March 12, 1971, p. 3862--Testimony of Lt. Col. L. Johnson.

[c] U.S. Senate, *Fiscal Year 1973* ..., March 7, 1972, p. 3544--Testimony of Col. James Hildebrandt.

[d] "Fairchild A-10," *Flight International*, March 20, 1976, p. 708.

Table A.2

GENERAL AIRCRAFT INFORMATION

Characteristic	YA-10	YA-9
Dimensions (ft)		
Length	52.6	53.5
Overall height	14.7	16.9
Wing height at centerline (CL)	5.3	6.9
Engine height-ground to inlet CL	10.4	5.3
Wing span	55	58
Main landing gear span (tire CL)	17.7	10.2
Engine CL distance from fuselage CL	4.7	3.9
Weight (lb)		
Design gross weight	29,800	25,860
Maximum gross weight	45,600	41,800
Useful load	20,500	18,720
Empty weight (gun, no ammo, 10 pylons, unusable fuel, pilot, flight test instrumentation)	23,800	23,730
Miscellaneous		
Total wing area (sq ft)	488	580
Flap total area (sq ft)	82.9	88
Total fuel capacity (lb)	10,010	9750
Uninstalled thrust per engine (lb)	9275	7500
Speed brake total area (sq ft)	92.4	102

development since early 1968 for the Navy's S-3A antisubmarine aircraft. GE had completed its 60-hour preliminary flight rating test (PFRT) a full 15 months before the YA-10's first flight, so there was little schedule risk associated with its selection. Some of the reasons Fairchild cited for mounting the engines in nacelles high and aft included a desire to minimize the possibility of foreign object damage to the engines, to reduce the likelihood that a single engine structural failure (e.g., from antiaircraft fire) would disable the other engine, and to permit a simple, uninterrupted structure.

In perhaps its key tradeoff, Northrop decided to use the lower-thrust Lycoming F102 engine and increase the wing span to achieve the desired turning, climb, and takeoff capability, thus saving about $140,000 per aircraft.[13] This selection was not without some risk because Lycoming had just 17 months to create the new engine by adding a fan to the T-55 turboshaft core section that it had used on many Army helicopters. The F-102 engine successfully completed its PFRT just two months before the YA-9's first flight.

Northrop incorporated an innovation that provided a capability unavailable on any previous aircraft. Its side force control (SFC) system allowed the pilot to make directional changes in the flight path during dive bombing without banking. Computer and simulator

[13]"Northrop Streamlines A-9A Management," *Aviation Week & Space Technology*, June 26, 1972, pp. 107-113.

studies accomplished before the prototype flight indicated that the feature might improve total weapon system bomb-delivery accuracy 20 to 30 percent. The SFC system, the extensive attention given to survivability, and the subsequent integration of the high velocity, high rate-of-fire, 30-mm GAU-8 gun with the A-10 airframe probably are the three most significant technical innovations in the AX program, which otherwise sought to combine extant performance capabilities into an aircraft optimized for the close-air-support mission.

Although not required and not originally planned for the prototype, Northrop also incorporated an APU on the YA-9. This unit not only provided a self-contained and self-sufficient engine starting capability, but unlike the YA-10 APU also drove an electric generator and hydraulic pump to facilitate aircraft servicing without the use of AGE.

The final principal design difference between the competitors was Fairchild's selection of a low-wing configuration that permitted it to hang the main landing gear from the wings, providing a particularly wide track for stability in operations from rough fields. Using the power of the TF34 engines to overcome added drag, each wheel only partially retracted into an aerodynamic pod below each wing, permitting an uncomplicated, low-cost wing structure. Because of Northrop's selection of a high-wing position, it chose to mount its fully retractable landing gear in the fuselage.

The contractors designed their prototypes to have the same general external configuration, propulsion performance, mass properties (through the use of ballast), and handling qualities as those anticipated for the production aircraft. Because both prototypes used off-the-shelf landing gear, they could not demonstrate the forward-basing capability required of the production aircraft. Unavailability of the 30-mm gun prevented its demonstration during the CPP. The prototypes also did not incorporate many of the survivability features of the production aircraft. Tables A.3 and A.4 summarize some of the more important differences between the prototypes and production aircraft.

The contractors did use the prototypes to test selected components or concepts they expected to use on the production AX. For example, Fairchild's production design made extensive use of swage fittings for the aircraft's hydraulic system, so they installed a dozen or so swage fittings on the prototype aircraft to evaluate their performance. Similarly, Fairchild used the prototypes to help determine proper hydraulic system filter sizes and to identify the most desirable hydraulic fluid for the production aircraft.

Building the Prototypes

Use of off-the-shelf items such as those listed in Tables A.3 and A.4 represents only one means by which the contractors minimized the costs of prototype construction. Using freehand sketches where practical, Northrop's tool design drawings incorporated only critical points, contours, or holes. Northrop tried to avoid making special tools whenever possible by using standard tools, rigging, or clamping. No provision was made for interchangeability of prototype components. When replacing assemblies, Northrop used coordinated drilling plates and tooling locators, hard points, and stops. With the "develop and install" and "cut and fit" concepts, it fabricated some parts oversize and trimmed them to fit.

Sheet metal parts were fabricated on soft tooling. Machined parts were substituted for more expensive precision forgings. Northrop used numerically controlled machine tools to make about 15 percent (by weight) of the prototype airframe. Although that was considered hard tooling, Northrop still had considerable flexibility to reprogram the numerically controlled machine tools and accommodate changes in any subsequent production article.

Table A.3

DIFFERENCES IN YA-9 PROTOTYPE AND ANTICIPATED PRODUCTION AIRCRAFT

System	Prototype	Production Aircraft
Air conditioning unit	Modified from Mitsubishi MU-2	New
Fuel system	No aerial refueling No external tank provisions Tank survivability items deleted	Complete fuel system
Main landing gear	Modified from A-4D	New
Avionics function	Off-the-shelf minimal avionics specified in RFP (UHF, Intercom, TACAN, IFF/SIF, MARS)	Production navigation, communication, and identification functions
Weapon delivery	F-5 Norsight No laser spot seeker or X-band beacon transponder	Dual reticle optical sight with HUD
Gun	20-mm M61A1	30-mm GAU-8

Northrop's overall prototype construction approach reflected its expectation of changes in a subsequent production design; it chose to defer substantial investments in tooling until the resolution of uncertainties in the flight test program. Northrop flew its first prototype 17 months after signing the competitive prototype phase contract,[14] with the second aircraft flying shortly thereafter. Although functionally the same, the two aircraft differed in some minor respects, including flight-test instrumentation and some material substitutions.

To achieve its early flight date, Fairchild constructed its prototype with a number of techniques similar to Northrop's. Prototype drawings in the form of layouts incorporated both engineering information and the data required to produce or procure detailed parts. Fairchild's fabrication plan included throwaway tooling, one-piece fixtures, 100 percent on-site airframe fabrication, and prototype equivalents for high start-up cost items—e.g., windshield, armor, forgings, avionics. Engineers deliberately overdesigned certain components to minimize the need for extensive structural testing.

Fairchild tried to minimize special tools and make maximum use of standard tools and tool designs, although specific tool designs were made for major assembly, subassembly, and master tools. Fairchild, like Northrop, fabricated sheet-metal skins oversize and trimmed

[14]The YA-9's first flight occurred on May 31, 1972. The first flight of the YA-10 occurred 20 days earlier.

Table A.4

DIFFERENCES IN YA-10 PROTOTYPE AND ANTICIPATED PRODUCTION AIRCRAFT

System	Prototype	Production Aircraft
Fuel system	No aerial refueling No external tank provisions Tank survivability items deleted	Complete fuel system
Landing gear	F-105 nose gear F-4C main gear	New
Avionics function	Off-the-shelf minimal avionics specified in RFP	Production navigation, communication, and identification functions
Weapon delivery	F-5 Norsight No laser spot seeker or X-band beacon transponder	Dual reticle sight or HUD
Gun	20-mm M61A1	30-mm GAU-8
Hydraulics	Reduced capacity pumps High-cost hardware for survivability deleted	Complete system
Structure	Certain survivability features deleted Local overdesign to ensure integrity without testing	Complete system
Engine	YTF34/F5	TF34-GE-100

them on installation. Attachment holes for rivets and bolts were incorporated during installation of sheet metal and machined details. To insure good fits without costly tool coordination, major splice holes were drilled undersize in details and were finish-bored after the details were installed and assembly was complete. Stopping short of capital investment in production tooling during the prototype phase, Fairchild judged its tooling adequate for building more than just two prototypes, but not suitable for high-rate production.[15]

[15]Hansen Woods, "A-10 Prototype Designed for Production," *Aviation Week & Space Technology*, June 26, 1972, p. 117.

Planning and Conducting the Test

The AX RFP established the general framework for the prototype test/evaluation program: a scheduled four- to five-month contractor flight-test program (Task I), and a two-month Air Force Flight Evaluation (AFFE) (Task II), all at the Air Force Flight Test Center, Edwards AFB, California. The test/evaluation requirements section of the RFP directed that during Task I the contractors should demonstrate flying qualities requirements, expand the flight envelope, evaluate ordnance separations, and deliver the prototypes to the Air Force for Task II testing. During the five months of Task I flight tests, the Northrop prototypes accumulated about 162 hours and the Fairchild prototypes about 190 hours. Contractor test pilots flew about 80 percent of the flights during Task I, and Air Force pilots the remainder. In accordance with the RFP, during Task I the contractors supplied the Air Force with flight test data, recommended aircraft operating procedures, aircraft limitations, and ordnance separation test results. The Air Force pilot participation in Task I, together with the data supplied by the contractors, assisted the Air Force in detailed planning for the Task II flight evaluation.

As the contractors accumulated information during Task I, they made some modest changes to enhance prototype performance in preparation for the flyoff. For example, Fairchild changed the angle of incidence of the stabilizer, added a speed brake preselect control to reduce pilot workload during weapon delivery, and modified the elevator trim tab to reduce stick forces in the manual flight control mode. On the Lycoming engine, a ring gear that coupled the fan to the core had a tendency to develop cracks. Lycoming added a damper to correct this reliability problem.

Contractors also deferred some changes. Fairchild designed its prototype with 40° of flap travel but discovered that 20° provided adequate performance. They elected to defer the change until full scale development. Northrop deferred downsizing the YA-9 flaps and changing the horizontal stabilizer even though it determined the 10° dihedral to be unnecessary.

The contractors also used the prototypes to obtain information about various changes they contemplated incorporating on the production aircraft. The YA-10 prototype had higher than expected pylon drag, so Fairchild fabricated and flight tested pylons made from structural steel, wood, and sheet metal to simulate the reduction in height and the faired attachment fitting of a low-drag pylon. Fairchild also made limited flight tests of some aerodynamic modifications to remedy an airframe/engine incompatibility problem.

Contractor testing proceeded smoothly, with the exception of a YA-10 landing accident in which both main landing gear tires blew out. The aircraft skidded off the runway, damaging the underside of the fuselage and the landing gear, but without damaging the basic wing and fuselage structure. Fairchild made repairs, including the installation of a new antiskid system, and returned the aircraft to flight status in about a month. Because of the rapid pace of Task I testing, both contractors delivered their prototypes to the Air Force for Task II testing two weeks ahead of schedule.

Although the competitive atmosphere seemed beneficial in most respects, some evidence suggests that it contributed to communication problems between the contractors and the Air Force. For fear of giving a competitive advantage to one contractor over the other, the Air Force was extremely reticent about giving candid answers to certain contractor questions. For example, Air Force test pilots were reluctant to give Northrop any comments about their preferences for control stick forces.

The reverse communication problem also existed. Reportedly, many contractor questions went unasked about an operating and support cost model supplied to the contractors by the

Air Force. Because the Air Force routinely supplied answers to one contractor's questions to the other competitor to clarify the problem to all parties concerned, contractors were reluctant to ask questions that might possibly compromise their competitive position.

For the AFFE phase, the AX RFP specified operating limitations, contractor maintenance support requirements, data instrumentation recording requirements, and a general description of the tests and evaluations to be conducted. The AFFTC, as directed by AFSC Headquarters, was responsible for formulating the detailed test plan and conducting the AFFE. Its objective was to determine the capabilities of the prototype aircraft and their suitability for the CAS mission. The Joint Test Force (JTF) assembled to achieve these objectives included representatives from the AFFTC, as well as from TAC, AFLC, and ATC. Upon conclusion of testing, the JTF supplied written reports and briefings to the Source Selection Evaluation Board and the Source Selection Advisory Council detailing the results of the flight evaluation.

To achieve the test objectives, the Air Force devised an extensive set of ground rules to insure a fair evaluation of the two prototypes. Before the flyoff, the five primary and two backup pilots flew a 125-hour weapon-delivery program in Cessna A-37B attack aircraft to verify the ground rules.[16] During the AX flyoff, pilots alternated between flying the two types of aircraft whenever possible, and rotated between flying lead and wing in the two plane formations. The YA-9 and YA-10 flew sorties together to equalize the effects of weather, wind, and turbulence conditions. Only on special operational suitability missions did two YA-9s or two YA-10s fly together.

The Task II flight test phase emphasized those aspects of aircraft performance critical to the successful accomplishment of the CAS mission. Table A.5 indicates that in a flight-test program of less than 300 hours, the Air Force devoted 60 percent of the total flight time to weapon delivery and TAC mission suitability testing. The bulk of the remainder of the flight testing was devoted to evaluating basic takeoff, landing, climb, cruise, and combat performance, as well as aircraft flying qualities. System evaluations accounted for only about 13 percent of primary flight time. The test emphasis mirrored the spirit of the RFP, which gave the contractors considerable freedom with systems while specifying aircraft performance requirements.

Weapon-delivery flight tests sought to determine bombing and strafing accuracy under a rigorous set of delivery conditions. Although primarily designed to detect differences in capability between the prototypes, the tests did provide some measure of combat realism, since delivery conditions included very short target tracking times (e.g., less than six seconds) and different headings or dive angles on each bomb-delivery pass. A timer limited gun bursts to 60 rounds per pass. The evaluators considered the percentage of bombs hitting within the lethal radii of a Mk-82 bomb, the percentage of bombing misses that might endanger friendly troops, and the percentage of strafing hits within a circle representing the vulnerable areas of a tank. Hence, after each aircraft had delivered more than 600 bombs and fired about 15,000 rounds of 20-mm ammunition, evaluators knew the prototypes' weapon-delivery accuracy for dive bombing and strafing with considerable confidence.

In still other mission-oriented testing, two TAC pilots, both flying either YA-9s or YA-10s, delivered live weapons against real targets on a range and flew strip alert, cruise and loiter, and helicopter escort missions as well as rendezvous missions with forward air controllers. The two TAC pilots, together with three AFSC pilots, constituted the project's prime

[16] "Tight Schedule Set . . .," *Aviation Week & Space Technology*, October 2, 1972, p. 46.

Table A.5

FLIGHT TEST ACTIVITY DURING THE AIR FORCE FLIGHT EVALUATION

Activity	Flight Time (Hours) YA-9	YA-10
Performance and flying qualities	51.5	42.5
Systems	12.7	13.7
Weapon delivery	62.7	60.7
TAC mission suitability	18.6	21.6
Total time	145.5	138.5
Total sorties	(123)	(87)

pilots. The TAC pilots split their time evenly with two AFSC pilots for the weapon-delivery evaluation, and overall, TAC pilots flew roughly 45 percent of the flight hours. Such heavy early involvement of the user command had not been the usual development practice before the AX flyoff.

Since flight time devoted specifically to system evaluation amounted to only about 10 percent total flight time, much of that evaluation effort consisted of monitoring system operation during other testing to provide qualitative observations of system performance. Some systems had little or no instrumentation; nonetheless, the limited flight testing, together with other ground tests, did illuminate a number of desirable and undesirable system features of both prototypes. For example, testing identified 74 items that would require mandatory correction on any production version of the YA-9 and 40 on the YA-10, ranging from unacceptable switch locations to a basic airframe/engine incompatibility. The JTF submitted System Evaluation Reports describing the deficiencies to the SPO during testing.

Although handicapped both by limited flying hours and by limited numbers of aircraft, the systems tests also included an evaluation of reliability and maintainability, even though contractor personnel did all aircraft servicing. A Maintenance Evaluation Team composed of AFLC, AFSC, and TAC personnel observed and recorded maintenance events and repair times to get rough estimates of scheduled and unscheduled maintenance requirements (e.g., maintenance manhours per flying hour) for each prototype. ATC personnel estimated the skill levels required to make repairs. The JTF submitted the results of the reliability and maintainability analysis to the SPO and to the Source Selection Advisory Council.

Competitive Flyoff Test Results

In most respects, the Air Force flight evaluation indicated that both prototypes demonstrated or exhibited the potential for acceptable performance in the CAS role. The YA-9 generally met or exceeded most air vehicle performance goals set in the RFP, although Table A.6 indicates the YA-9 did marginally fail to meet the landing distance goal at the forward airstrip weight. The YA-10 fell short of several speed, maneuverability, and takeoff goals.

Both prototypes demonstrated a number of desirable system features, including such

Table A.6

PERFORMANCE DEMONSTRATED BY THE PROTOTYPES

Parameter	Goal	YA-9	YA-10
Speed (kn)			
Maximum level flight speed at 5000 ft	350	378	(a)
Maximum level flight speed, clean, sea level	400	410	350
Cruise speed at 5000 ft	300	(a)	281
Maneuverability (gs)			
Sustained load factor, 150 kn	2.2	2.6	2.2
5000 ft, 275 kn	3.5	4.2	3.0
Instantaneous load factor, 150 kn	2.2	2.6	(a)
5000 ft, 300 kn	5.0	7.0	5.8
Airport Performance (ft)			
Takeoff ground roll, forward airstrip wt	1000	750	1240
Landing ground roll, forward airstrip wt	1000	1170	1050
Weapon Delivery			
Bombing circular error average (ft)			
overall	none	114	109
optimum release conditions	none	41	44
Strafing average percentage of hits			
15° dive	none	53	61
45° dive	none	22	18

(a) Data not available.

things as excellent bombing and strafing accuracy, armament control, cockpit visibility and maintainability. Notwithstanding these desirable features, the flight evaluation did identify several deficiencies that might have posed serious problems had they been discovered later during a more conventional development program. Table A.7 highlights some of the more significant deficiencies identified by Air Force evaluators during the competitive flyoff.

Under flight test conditions, the YA-9's side force control (SFC) system did not live up to expectations. In some situations it tended to increase pilot workload and degrade weapon-delivery accuracy. When it did function properly, it did not greatly improve weapon-delivery accuracy. Since the aircraft handled well without the SFC system, midway through the comparative weapon-delivery program, the Air Force approved Northrop's request to discontinue its use. In the test atmosphere, the Air Force and the contractor were able to test and rejected a technological innovation without having to undergo a contract renegotiation, a specification change, or other difficulties that might have come up had the problem occurred during a more traditional development program.

Seeking increased agility, Northrop engineers developed a very sensitive control system having light stick forces and stability margins near the lower bound allowed in military specifications. During pullups in high-speed, high-dive-angle weapon-delivery tests, pilots tended to exceed the aircraft's load factor limit even when making only small longitudinal stick movements. Under test ground rules, the Air Force allowed contractors to make con-

Table A.7

SIGNIFICANT DEFICIENCIES REVEALED DURING PROTOTYPE TESTING

Airframe	Cockpit	Flight Controls	Avionics
		YA-9[a]	
	Uncomfortable ejection seat	Rudder force unacceptably high after loss of right hydraulic system Longitudinal control system unacceptable for high speed weapon deliveries[b] Side force control ineffective[c]	Unacceptable heading and attitude reference system operation
		YA-10[d]	
Engine/Airframe Incompatibility	General accessibility of cockpit controls inadequate Uncomfortable ejection seat	Flying qualities unacceptable in manual reversion (pitch) during landing	Unacceptable heading and attitude reference system operation

[a]Frank N. Lucero et al., *A-9A Flight Evaluation* ..., AFFTC-TR-73-2, March 1973, p. 9.
[b]A modification during testing corrected this deficiency.
[c]SFC system discontinued during testing.
[d]Frank N. Lucero et al., *A-10A Flight Evaluation* ..., AFFTC-TR-73-3, March 1973, p. 9.

figuration changes during the flyoff if safety of flight considerations were involved. As a consequence, the Air Force approved a Northrop modification to the control system that increased stick forces slightly. Weapon-delivery tests began again after a two-week suspension. Since the contractor considered the fix less than optimum, subsequent refinement of the correction probably would have taken place had Northrop won the competition. In any case, the prototype served to identify the problem early in development.

One fundamental and unexpected problem encountered by the YA-10 during testing illustrates the value of the prototyping strategy perhaps better than any other. Task I contractor testing indicated that the YA-10 engines tended to stall and flame out at high angles of attack during accelerated maneuvers. Excessive turbulence at high angles of attack from the fuselage/wing root area disturbed the engine-inlet-flow field, which caused engine compressor stalls and subsequent overtemperature conditions. Although some preliminary testing was done during Task I, Fairchild did not have time to refine an aerodynamic modification to solve the problem before Task II testing. As a temporary fix for Task II testing, and to protect the engines, the airframe and engine manufacturers developed an inlet disturbance detection system that automatically cut back engine power before stall occurred. Since the CAS mission requires operations at high angles of attack near stall at low altitudes during weapon-delivery pullouts and sustained maneuvering, the loss of power associated with the engine protection system represented an unacceptable solution. Hence, the viability of Fairchild as a competitive contractor for the AX depended upon its developing an adequate solution.

After extensive wind-tunnel testing of various corrective measures, Fairchild proposed, and the Air Force approved, the modification of one prototype to incorporate fixed leading-edge slats, stall strips, wing/fuselage fillets, and vertical strakes on the fuselage. Tests conducted with the modified prototype shortly after the completion of Task II testing indicated satisfactory engine operation during all maneuvers. During DT&E/IOT&E, the Air Force later successfully flight tested variable leading-edge slats triggered by an angle-of-attack sensor.

Thus, in a highly competitive test environment, the contractor used the prototype to identify a very serious deficiency and test and verify a correction for the deficiency long before the first DT&E aircraft had rolled off the production line. In the absence of the prototype, the problem might not have surfaced until much later in development, perhaps causing a major program crisis like the one in the F-111 program caused by another airframe/engine incompatibility.

This example also provides a strong argument against those who contend that detailed contract definition studies using exhaustive engineering and wind-tunnel analyses can surface nearly all major fundamental problems before the first flight of a development aircraft. Fairchild obviously believed they could make their proposed propulsion configuration work satisfactorily, and their proposal documentation indicated that the predictions were based on extensive wind tunnel measurements of engine inlet flow fields at high angles of attack. Northrop, however, specifically rejected the aft engine location, stating in their proposal:

> The "Low-Wing Aft Engine" aircraft was rated high in almost all areas, but "low" in the Propulsion System Operation category and "low" in Handling Qualities. The uncertainty associated with the propulsion system is the potential problem concerning airflow distortion at the engine inlet in a highly maneuverable aircraft such as the AX. The magnitude of these problems and potential difficulties cannot be adequately assessed without extensive test data and perhaps would not appear until actual flight test at high "g" loadings.

The example illustrates that two competent aerospace firms can arrive at different configurations based on wind tunnel tests and engineering analyses. Fairchild's experience with

the YA-10 reinforces the notion that these analyses cannot always identify fundamental problems (e.g., an airframe/engine incompatibility) before an aircraft flies. In such a circumstance, the prototype becomes a particularly valuable tool for resolving uncertainties and differentiating between alternative configurations before making production commitments.

Source Selection

Although the Air Force used Task II flight-testing results as inputs to the source-selection process, the contractors relied on their Task I test results in responding to the full scale development RFP.[17] The story behind the drafting of the RFP for full scale development provides the first evidence of the shift in orientation away from the austere prototype approach to the more usual weapon-system development practices.

The streamlined prototype phase RFP had made few demands for subsystem testing or compliance with military specifications. In drafting the RFP for FSD, SPO engineers included all these requirements, and the RFP grew to include an extensive data package that described in exhaustive detail what the Air Force wanted in its production CAS aircraft. However, the Office of the Assistant Secretary of the Air Force for R&D directed that the SPO delete much of the specificity in the RFP. The AX SPO complied, but both contractors' proposals were generally responsive to the more extensive requirements of the original draft, even at the expense of some increased costs.

In responding to the RFP for FSD, Fairchild proposed a number of changes in moving from the prototype to production configuration, including many prompted by knowledge gained in prototype flight testing. For example, it planned to incorporate the aerodynamic modification to remedy the airframe/engine incompatibility. Fairchild designed a new cockpit for the production aircraft because of complaints about accessibility in the prototype, and replaced the F-105 ejection seat with an Escapac-series seat. The production aircraft would also have control system refinements, low-drag pylons, a tail-plane rake-angle change, and a reduced maximum flap deployment angle. Because prototype flight testing indicated it had designed for more wing bending than actually experienced in flight, Fairchild incorporated a wing-tip extension that increased the span by 30 inches and reduced induced drag. Moreover, to reduce engine costs, Fairchild proposed using a modified version of the TF-34 engine that deleted or simplified a number of features required for the Navy application, as well as the other system changes noted in Table A.4.

Northrop deleted the SFC system from its proposed production aircraft and incorporated control system refinements. It downsized speed brakes, flaps, and the environmental control system, and removed the dihedral from the horizontal stabilizer. The production aircraft's wing was to have a more uniform taper to reduce costs. Of course, Northrop also planned the other system changes noted in Table A.3.

Northrop made extensive use of the prototype experience in estimating the costs of the production aircraft for its proposal, and we expect that Fairchild did the same. Northrop

---

[17] The Air Force required that the contractors submit proposals for full scale development *before* the Air Force flight evaluation began. "The reason behind having the early proposal submittal is to allow time for an orderly evaluation of their contents during prototype testing and to insure that they are generated while there is still a viable competition between the A-9 and A-10." (U.S. Senate Committee on Armed Services, *Fiscal Year 1973 Authorization for Military Services ...*, Hearings, 92d Cong., March 7, 1972, p. 3554—Testimony of Col. James Hildebrandt.) The Air Force did allow the contractors to submit amendments to the proposals near the end of the Air Force flight testing.

made detailed cost estimates using the prototype hardware rather than just using parametric cost models. Manufacturing engineers physically went over the prototypes to judge the size and quantity of tools required for rate production. They looked at the routing of lines to see how many brackets would be required, and counted parts. Northrop contends having prototype hardware helps it eliminate the oversights that commonly occur when costing a "paper" airplane design. Of course, because prototype manufacturing and assembly techniques differ from those used for high-rate production, contractors could not directly estimate manufacturing labor costs from the prototype experience.

Northrop also indicated it incorporated in its proposal reliability and maintainability (R&M) data gathered during testing for those systems common to the prototype and production aircraft. Northrop particularly used the R&M data collected for the Lycoming engine.

To make the source-selection decision, the Air Force considered (1) operational capability, (2) transition risks in going from the prototype to the production configuration, (3) soundness and adequacy of proposal data not demonstrated as part of the flight evaluation, and (4) program costs. The flight evaluation probably contributed most to deliberations about the operational capability of the two contenders, since the Air Force could compare demonstrated prototype performance with the promises made in the contractor's proposals for full scale development.

On January 18, 1973, the Air Force announced the selection of Fairchild's A-10 as the winner of the CPP. A subsequent review of the source-selection decision by the GAO provided some details about the rationale the Air Force used in selecting the A-10.

In the words of the GAO, "Because both contractors developed acceptable prototype aircraft, the competition was quite close." In making its selection, the Air Force said that proceeding into full scale development would be less costly for the A-10 and could be accomplished within authorized DoD funding constraints. Although the A-9 prototype generally exhibited somewhat better air vehicle performance than the A-10 prototype, the Air Force believed certain A-10 features made it more operationally suitable for the CAS mission than the A-9. The Air Force cited such attractive features as the higher engine placement of the A-10, which minimized the possibility of foreign object damage. The engine placement and low-wing configuration of the A-10 also permitted wider pylon spacing, which provided more armament-carrying flexibility and made weapon loading easier. The Air Force also believed the A-10 would exhibit better maintainability and survivability than the A-9. It expected a smoother transition from the A-10 prototype to the production phase because of the prototype's similarity to the anticipated production configuration. The similarity made the YA-10 particularly attractive, since the Air Force believed it could use the YA-10 immediately for a broader set of developmental and operational flight tests before the production decision than would be possible with the YA-9.[18]

One of the reasons the Air Force cited for selecting the A-10 for development illuminates an interesting dilemma for a contractor involved in a competitive prototype program. In assessing the number of changes and the risks associated with the changes required for transition from a prototype to production configuration, the Air Force preferred the Fairchild aircraft because of the aforementioned similarity between the prototype and proposed production aircraft. To be favorably judged in a prototype competition that incorporates this source-selection criterion, a contractor must balance his desire to minimize the appearance of transition risks with his natural tendency to exploit the knowledge gained from prototype testing

[18]U.S. General Accounting Office, letter to Senator Lowell Weicker, Jr., of Connecticut, B-173850, 11 April 1973, pp. 2-4.

to incorporate changes that yield a better production product. The evaluator must then carefully weigh whether the benefit derived from each proposed change is worth the risk associated with the change.

Using the YA-10 During Development

In addition to using the prototype flight-test results in source selection, the Air Force used its experience from Task II testing in negotiating the full scale development contract with Fairchild.[19] Based on their flight-test experience and other analyses, the contractors submitted trade studies and supporting rationale for deviating from some of the requirements outlined in the AX Acquisition Program Proposal Instructions. Having performance information based on tests with actual hardware gave the contractors a firm, rather than speculative, base from which they could estimate the possible cost and operational effects of relaxing, strengthening, or eliminating a requirement (e.g., the changes necessary to meet the 400-kn combat-speed goal). Similarly, AFFE results enabled the Air Force to understand how a proposed change in requirements would affect the operational capability of the system.

Working under a design-to-cost philosophy and knowing what the prototype had and had not achieved, the Air Force and Fairchild negotiated a number of changes, some of which are shown in Table A.8. For example, Fairchild determined the changes required to achieve the original combat speed requirements would not be cost effective. The small speed gain would require making major changes to the basic airplane configuration (e.g., reduced wing area or

Table A.8

SELECTED CHANGES IN ORIGINAL PRODUCT SPECIFICATION

Performance Item	Original Requirement (May 1970)	Negotiated Product Specification (Dec. 1972)
Airport Performance		
Forward airstrip takeoff distance	1000 ft	1050 ft
Forward airstrip landing distance	1000 ft	1050 ft
Maximum weight takeoff distance	4000 ft	3660 ft
Maximum weight landing distance	4000 ft	2600 ft
Speed		
Maximum combat speed (sea level, clean)	400 kn	390 kn
Cruise speed (5000 ft altitude)	300 kn	325 kn
Maneuverability		
Sustained load factor at 150 kn	2.2 g	2.4 g
Instantaneous load factor at 300 kn	5.0 g	6.5 g

[19]The Air Force negotiated a cost-plus incentive fee contract for the development and fabrication of ten RDT&E A-10 aircraft and fatigue and static test articles. In FY 1974, the Congress deleted funding for four of the RDT&E aircraft (*A-10 SAR*, July 5, 1977, p. 7).

smaller fuselage frontal area) to the detriment of other performance and cost goals, or developing a growth version of the A-10's engine. The Air Force judged the change in maximum speed to have only a minor impact on operational capability, and, as a result, reduced the requirement.

Using its flight-test experience with the prototypes, TAC also made inputs to the negotiations. Perhaps influenced to some extent by the YA-9's pressurized cockpit and the auxiliary power unit that drove hydraulic pumps and electric generators for self-contained aircraft maintenance, TAC specified that Fairchild incorporate these features on its aircraft. TAC also rejected Fairchild's proposal to use a fixed, bolt-on, aerial-refueling probe in place of the Universal Air Refueling Receptacle Slipway Installation used by other Air Force aircraft. The net result of the contract negotiations was a production aircraft having only modest net weight and external dimensional differences from the prototype, as shown in Table A.9.[20]

Table A.9

PROTOTYPE AND PRODUCTION AIRCRAFT CHARACTERISTICS

Characteristic	YA-10	A-10A
Dimensions (ft)		
Length	52.6	52.6
Height	14.7	14.7
Wing span	55.0	57.5
Main landing gear span	17.7	17.3
Wheel base	19.3	17.8
Weight (lb)		
Maximum gross weight	45,600	47,400
Weight empty	18,790	20,800
Miscellaneous		
Total wing area (sq ft)	488	506
Flap area (sq ft)	82.9	86.0
Speed brake area (sq ft)	92.4	86.8
Total fuel capacity (lb)	10,010	10,700
Uninstalled thrust per engine	9275	9065

The Air Force used the two YA-10 prototypes extensively for DT&E and IOT&E flight testing until delivery of the first full scale development DT&E aircraft. By the time the Air Force placed both prototypes in flyable storage in June 1975, they had accumulated 1139 flying hours in 821 flights over 37 months. Joint DT&E and IOT&E Phase I testing by contractor, AFSC, TAC, and AFTEC pilots accounted for 797 flight hours, between March 1973 and June 1975. The prototypes proved valuable in the qualification of production equipment, in the conduct of operational tests not undertaken during the competitive flyoff, and in the evaluation of alternative design approaches to fix deficiencies revealed during the flyoff.

Table A.10 illustrates the spectrum of test activities conducted with the prototype during

[20]Two of the more noticeable dimensional changes were the wing-tip extensions and the shorter wheel base, the latter change being an attempt to enhance elevator authority during takeoff.

development, including a congressionally mandated flyoff with the A-7D. Without question, the prototype was most useful in the evaluation of the airframe/30-mm gun integration. The dramatic physical differences in the 30-mm GAU-8 and the 20-mm gun fired in the competitive flyoff introduced a number of uncertainties resolvable only by flight testing.[21] Uncertainties associated with the integration included the effect of gun gas filtering into the engine, the ability of the aircraft structure to withstand the 16.000 lb recoil loads, the aiming accuracy of the aircraft/gun combination during firing, and the effect of gun firing on other aircraft systems.

Table A.10

YA-10 TESTING DURING FULL SCALE DEVELOPMENT

- o YA-10 Airframe/GAU-8 Gun Compatibility Tests
- o Stores Carriage/Separation Tests
- o Preliminary Evaluation of In-flight Refueling Capability
- o Definition of Stall/Post-Stall Spin Characteristics
- o Maintainability/Reliability/Supportability Testing
- o A-7D/YA-10 Flight Evaluation
- o Icing Flight Tests
- o Evaluation of Selected Production Avionics
- o Air Loads Testing
- o Evaluation of Aural Stall Warning Device
- o Evaluation of Control System Modifications
- o Evaluation of Aerodynamic Slats
- o Evaluation of Drag Reduction Options

The first series of in-flight firing tests of the GAU-8 on the YA-10 took place during February and March 1974, one full year before flight of the first full scale development DT&E aircraft. The tests revealed one easily correctable problem—the gun installation was depressed an undesirable two degrees from the horizontal fuselage reference line—and one major problem—secondary gun-gas ignition (SGGI). At high gun-firing rates (4200 shots per minute), unburned gun gases collected and ignited in front of the gun muzzles, forming a fireball, interfering with pilot vision, and making the aircraft more visible in flight. More important, under certain conditions, the airstream carried the hot burned gases into the engines, causing compressor stalls. Photographs taken during CPP testing had indicated a potential ingestion problem by showing that approximately one-third of the 20-mm gun gas flowed over the YA-10's wing into the engine.

In an attempt to control the SGGI, the Air Force and Fairchild used the prototype to test a number of gun-gas-deflector devices similar to the deflector used on the YA-9. Ultimately rejecting this approach, the Air Force instead adopted ammunition using an SGGI inhibitor. The addition of the chemical inhibitor to the ammunition solved the SGGI problem but caused a residue deposit on the aircraft that diminished pilot visibility and created concern about corrosion and thrust degradation. Although the contractors had not completely re-

[21]Although the 30-mm gun was not ready for integration when the airframe contractors designed, built, and flew their prototypes, the AX SPO Director indicated that the SPO arranged monthly meetings between the two gun and two airframe contractors during the prototype phase to consider far more detailed issues than simple matters of weight and space provisions.

solved this problem by the time the Air Force stopped using the prototypes, the aircraft did contribute to an early identification of the problem and served as a testbed in evaluating alternative approaches to solve the problem.

The evidence suggests that the prototypes served as useful tools for revealing oversights and reducing important technical uncertainties early in the program. Both contractors extensively used prototype test results in refining their design proposals for full scale development. The YA-10 airframe/engine incompatibility revealed during prototype testing reinforces the notion that even careful engineering analysis can miss complex system interactions that only become apparent during flight testing. The test results in Table A.11 suggest that because of the similarity between the YA-10 and the production aircraft, the Air Force knew, even during the competitive prototype phase, the general class of performance it could expect from the A-10 system.

Table A.11

PROTOTYPE AND PRODUCTION AIRCRAFT PERFORMANCE

Performance Item	YA-10	A-10A
Cruise speed (5000 ft altitude)	281 kn	342 kn
Maximum level flight speed (Sea level, no bombs)	350 kn	368 kn
Sustained load factor		
(5000 ft altitude, 150 kn)	2.2 g	2.0 g
(5000 ft altitude, 275 kn)	3.0 g	3.2 g
Instantaneous load factor (5000 ft altitude, 300 kn)	5.8 g	5.7 g
Airport performance		
Takeoff ground roll (forward airstrip weight)	1240 ft	1900 ft
Landing ground roll (forward airstrip weight)	1050 ft	1460 ft

The air vehicle performance achieved by the production aircraft and shown in Table A.12 has fallen somewhat short of expectations formed at the beginning of full scale development, particularly in the area of takeoff and landing performance.[22] Conversely, weapon-delivery accuracy, particularly for the 30-mm gun, has far exceeded expectations. The evidence suggests that the performance shortfalls reflect the Air Force's willingness to make modest but operationally acceptable sacrifices in performance to keep costs of the A-10 system under control.

[22]Several factors collectively contributed to the airport performance shortfall: The production engine developed less thrust than expected, the production aircraft weighed more than anticipated, the drag reduction program fell short of its goals, and moving the landing gear forward 1.5 ft did not increase the elevator authority at takeoff as much as expected.

Table A.12

A-10 PERFORMANCE RELATIVE TO INITIAL DEVELOPMENT ESTIMATES

Performance Item	FSD Product Specification (Dec. 1972)	Demonstrated Performance (Jan. 1976)	Outcome Factor[a] (Value greater than 1 indicates better than expected performance)
Speed (knots)			
Cruise speed (5 kft)	325	342	1.05
Maximum combat speed (SL, no bombs)	390	368	.94
(5 kft, 6 bombs)	385	368	.95
Maneuverability (gs)			
Sustained load factor (150 kn)	2.4	2.0	.83
(275 kn)	3.5	3.2	.92
Instantaneous load factor (300 kn)	6.5	5.7	.88
Airport performance (feet)			
Takeoff ground roll (forward airstrip weight)	1050	1900	.55
(maximum weight)	3660	4850	.75
Landing ground roll (forward airstrip weight)	1050	1460	.72
(maximum weight)	2600	4000	.65
Mission performance			
Close air support loiter time (hr)	2	1.8	.90
Ferry range (n mi)	2300	2160	.94
Weapon delivery			
Bombing accuracy, Mk 82 (CEP) (ft)	112	101	1.11
Strafing accuracy (CEP) (mils)	10	4	2.50

[a]The outcome factor is computed as the ratio of the actual to the product specification value of the performance item at the beginning of development.

THE TRANSITION TO PRODUCTION

Although the AX competitive prototype phase successfully achieved nearly all its testing objectives and met cost and schedule goals, Fairchild's difficulties in making the transition to production suggests that at least one aspect of a contractor's capabilities does not get fully demonstrated during prototyping: its ability to successfully manage the transition from the prototype to the high-rate production phase of a large program. Certainly a prototyping strategy is far more an exercise in development than in production; the management, design, and construction approaches used by the two contractors to deliver their prototypes at low cost in a short period of time differed greatly from high-rate production practices. A recounting of Fairchild's difficulties in making the transition to production highlights this potential problem area.

In mid-1974, the Air Force Plant Representative Office (AFPRO) at Fairchild Republic issued an internal report criticizing Fairchild's inexperienced management, organizational structure, plant and machinery, and its disproportionately old production work force.[23] Although at least two studies examining Fairchild's production capacity had been conducted previously, apparently neither seriously questioned Fairchild's ability to manage the A-10 program.[24]

Fairchild Republic had delivered its last F-105 nearly 10 years earlier. During the previous ten years the company had modified some F-105s to the Wild Weasel configuration but had been existing mainly as a subcontractor for various military, civilian, and space programs (e.g., F-4 rear fuselages, 747 flaps, space-shuttle fins). During the prototype phase, Fairchild functioned adequately, but as it started gearing up for A-10 production, some shortcomings became apparent. Management was decentralized and inexperienced with sophisticated production programs. Its work force, composed of those who had enough seniority to weather Fairchild's lean years, averaged 54 years old. The Long Island plant was small and much of its capital equipment was from 10 to 30 years out of date.

Following the AFPRO report, a high-level review, headed by Lt. General Robert E. Hails, USAF Vice Commander, TAC, Langley AFB, evaluated "government and contractor management, the financial position of the company, manufacturing capability and facilities, quality assurance procedures, schedules, and flight operations." After an intensive study, the Hails commission concluded "that the A-10 program is sound and that production can begin."[25] The report's optimistic conclusion was tempered somewhat by its recommendation that both the government and Fairchild substantially overhaul the program management and that significant production changes be made to insure program efficiency.

By mid-November, the Air Force had appointed Colonel Jay Brill, Deputy Chief for Systems, AFSC, as A-10 SPO director, and Colonel Merton Baker, "the most experienced AFPRO

---

[23]Warren C. Wetmore, "A-10 Program . . . Reshaped," *Aviation Week & Space Technology*, February 10, 1975, pp. 44-47.

[24]The *AX RFP* explicitly stated that, among other things, "Any prospective bidder . . . must have experience in the management of the development, test, production, and delivery of a modern weapon system program of the magnitude envisioned for the AX aircraft (and) must have, or have the means to obtain, the critical physical facilities required for the design, fabrication, test and production of both the prototype and production model AX aircraft." Therefore, before source selection, the Air Force commissioned studies to evaluate each competitor's ability to produce ten DT&E and 48 production AXs. The Defense Contract Administration Services Office (DCASO) surveyed the Fairchild facilities and its findings were submitted to and accepted by the Air Force. Their acceptance and the subsequent selection of the A-10 suggest that the Air Force considered Fairchild capable of performing the task. During later Senate testimony, however, the Air Force conceded that the initial review had been conducted by persons selected for convenience, rather than for any "uniquely required qualifications."

[25]"DoD Statement on A-10 Program," *Aerospace Daily*, Nov. 18, 1974, p. 94.

in the AFSC,"[26] as the AFPRO at Fairchild. The Air Force restructured the relationships among the SPO, the AFPRO, and the Air Force Contract and Management Division, formalizing areas of responsibility and reporting schedules. It gave Brill and Baker expanded staffs with increased responsibilities for A-10 production.

Fairchild responded by reorganizing its Republic division, making the A-10 program directly accountable to a newly created Office of the President. Within the new management framework, Fairchild assigned higher priority to quality assurance and procurement responsibilities, as well as to integrated logistics support. It brought new managers with recent production experience into the division in key positions. In a move apparently considered before the management changes, Fairchild announced it would transfer final assembly of the airframe from the smaller Long Island plant to its plant in Hagerstown, Maryland. It claimed the move would have the double advantage of providing better flight-test facilities at a considerable saving in overhead expenses. Finally, Fairchild planned to double its five-year capital budget by investing in new plant and equipment.[27]

These changes, recommended by the Hails Committee, expanded the government's role in all aspects of A-10 management and production. The SPO abandoned the low profile it had maintained during the prototyping phase. By early 1975, following the reorganization, the Air Force had assigned 114 SPO personnel to the production section—up from 34. The SPO and AFPRO, under the guidance of Headquarters AFSC, developed areas of responsibility and formal reporting procedures "to insure optimum involvement in manufacturing operations" and to monitor "the overall financial condition of Fairchild Industries."[28] The resulting A-10 program bore little resemblance to the program as it existed during the prototype phase or to the originally planned production program. Shortly after the end of the prototype phase, the AX SPO Director, Colonel Hildebrandt, testified before Congress that a "very significant advantage of the prototype phase is the opportunity it affords the contractors and the government to form and exercise their program management teams prior to committing the responsibility for conduct of the major effort to them."[29] We can conclude that Fairchild's production transition problems, which became apparent about a year and a half *after* the AX SPO Director testified, do not provide very strong evidence of a significant carryover in contractor management and production experience from the prototype to high-rate production phase. That is to say, prototyping and production phases can use such different management approaches that a contractor's success in the management of a prototyping phase does not necessarily guarantee a smooth transition to production.

PROGRAM SCHEDULE PERFORMANCE

The YA-10 prototypes helped to identify and focus attention on unforeseen technical problems in a timely manner during flight testing. The full scale development schedule experience reflects this fact in that no significant program delays in the delivery of DT&E aircraft can be directly attributed to technical problems. To understand how the schedule

---

[26]U.S. Congress, House Committee on Appropriations, Subcommittee on DoD, *DoD Appropriations for 1975 . . .*, Hearings, 93d Cong., 2d Sess., April 30, 1974, p. 856.

[27]Warren C. Wetmore, "A-10 Program . . . Reshaped," *Aviation Week & Space Technology*, February 10, 1975, p. 46.

[28]U.S. Senate, Committee on Armed Services, *Fiscal Year 76 and 7T Authorization for Military Procurement . . .*, Hearings, Part 5, p. 4266.

[29]U.S. Senate, Committee on Armed Services, Ad Hoc Committee on Tactical Airpower, *Fiscal Year 1974 Authorization for Military Procurement . . .*, Hearings, Part 5, p. 4498—Testimony of Col. J. Hildebrandt.

allowed for the early resolution of technical problems, we will examine the timing of program testing relative to the three major DSARC reviews.

The A-10 production schedule slipped, and two factors seem most responsible: (1) an early OSD decision that reduced the planned peak-production rate to ease the financial and management burden on the contractor, and (2) economic escalation that has forced repeated program stretchouts to keep within available funding limits. We will assess how these and other factors contributed to A-10 schedule slippage.

Test Scheduling Relative to DSARC Milestones

The A-10 underwent considerable flight testing before each of the DSARC decision points. As shown in Fig. A.3, the Air Force had completed the two-year competitive prototype phase, including about six months of flight testing (two months for the competitive flyoff) before the DSARC II go-ahead for full scale engineering development. Serving as test aircraft

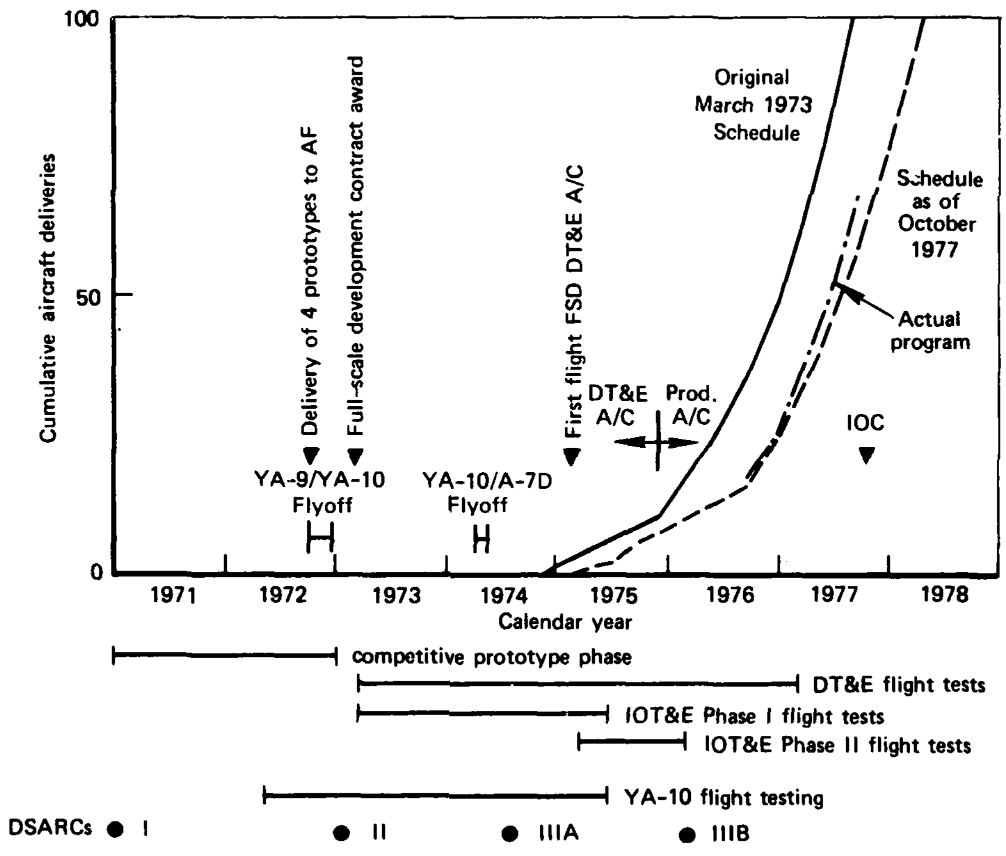


Fig. A.3—Testing and production schedules for the A-10 program

before the delivery of the first full scale development DT&E aircraft, the two A-10 prototypes had undergone 16 months of DT&E and IOT&E flight testing before the initial production go-ahead decision (DSARC IIIA), including initial in-flight firing tests of the GAU-8 gun.

Despite the considerable testing the prototype had undergone before the DSARC IIIA decision, the fact that DSARC IIIA occurred seven months before the flight of the first FSD DT&E aircraft did not escape the critical attention of Congress. Reviewing the A-10 development schedule before DSARC IIIA, Representative Joseph Addabbo (D-NY), charged: "The A-10 schedule . . . not only illustrates massive concurrency, but actually shows that production will be initiated before the first DT&E aircraft will be available."[30]

Lieutenant General W. J. Evans, Air Force Deputy Chief of Staff for R&D, responded by explaining that the program's technical risks had been reduced because of prototyping. "Therefore, we do not attach to the first flight of the DT&E aircraft any significant weight."[31] Thus, General Evans saw no contradiction in the A-10 schedule and the "fly-before-you-buy" concept.

After the DSARC IIIA review was convened in July 1974, the Deputy Secretary of Defense directed the Secretary of the Air Force to proceed with initial production of the A-10 by procuring 52 aircraft, subject to keeping a 28-aircraft-buy option open until the completion of certain critical milestones.[32] By late December, the Air Force received approval to go forward with the full 52-aircraft-buy after completing all the DSARC IIIA milestones, including successful production engine qualification tests.

The OSD gave the go-ahead for rate production (DSARC IIIB) just before the completion of IOT&E Phase II flight testing. Figure A.4 indicates that at the time of the DSARC IIIB decision the prototypes and development aircraft had logged about 2200 flight-test hours, split about evenly between the YA-10s and the A-10As. But because OSD made the decision before the completion of DT&E testing, there is no clean break between development and production in the A-10 program. Nevertheless, by using the YA-10 for early testing, the A-10 program accumulated nearly *three years* of DT&E and IOT&E testing before the DSARC IIIB decision (see Table A.13), whereas the F-15 rate production decision came only *seven months* after the beginning of testing. The F-16 decision came just *ten months* after the beginning of the DT&E flight testing and preceded the beginning of the IOT&E testing by about nine months.

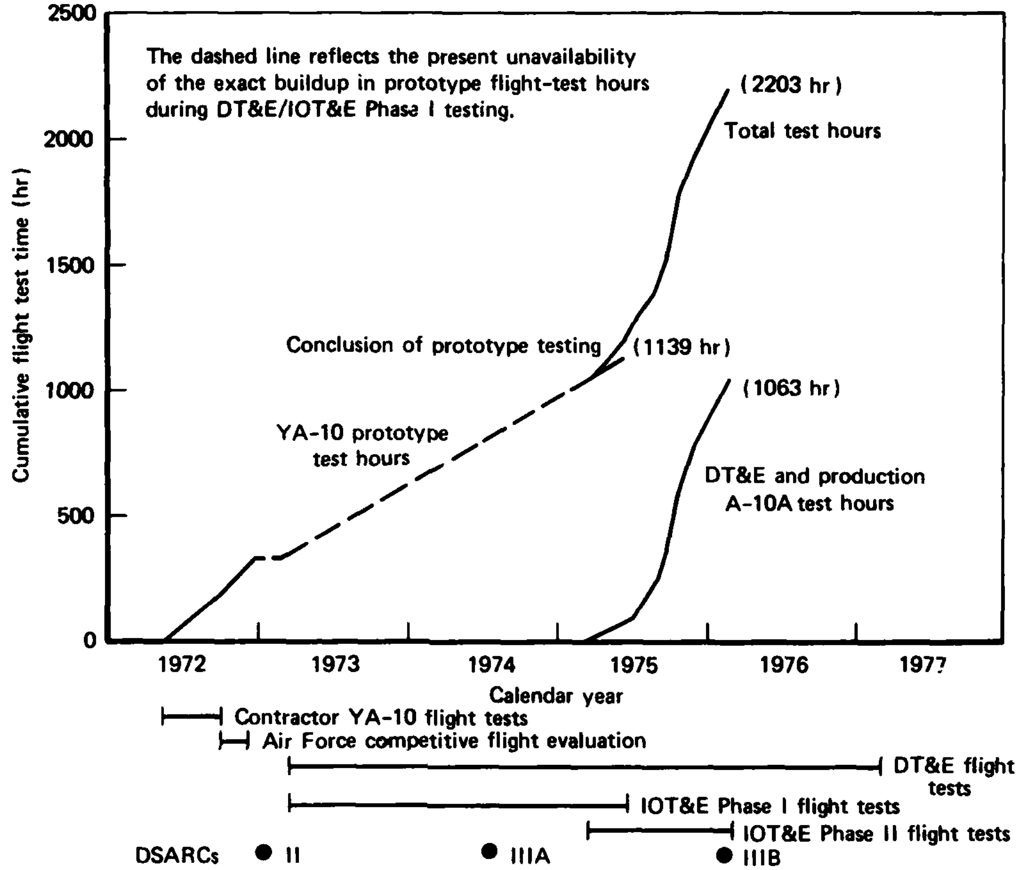
Although the A-10 testing before DSARC IIIB seems impressive when measured against other Air Force programs, some questions still remained unanswered when OSD approved the buildup to rate production. Less than five months before the decision, the A-10 fatigue test article had a fuselage failure. Fairchild developed, and the Air Force approved, a retrofit and redesign within the existing frame forging design and aircraft dimensions; but the new component test article did not undergo tests until *after* the DSARC IIIB decision had been made.

Prototype phase and DT&E testing had also identified some deficiencies that had not been corrected before the DSARC IIIB decision, including a marginal single-engine-climb capability under heavy gross weight conditions, and a lack of natural stall warning. By the time the Air Force had completed DT&E flight testing, one year after the DSARC IIIB deci-

[30]U.S. Congress, House Committee on Appropriations, Subcommittee on DoD, Hearings on *DoD Appropriations for 1975* . . ., Part 4, 93d Cong., 2d Sess., April 30, 1974, p. 856.

[31]Ibid.

[32]"Decision on A-10 . . .," *Aviation Week & Space Technology*, July 1, 1974, p. 23; and "A-10 Funding," *Aviation Week & Space Technology*, July 29, 1974, p. 14.



NOTE: The flight test hours for the FSD DT&E and production A-10s include the flying hours accumulated after Air Force acceptance at Edwards AFB. The contractor may have logged a modest number of hours prior to delivery of these aircraft to the Air Force.

Fig. A.4—Flight test time history for the YA-10/A-10A

Table A.13

TESTING BEFORE DSARC IIIB

Aircraft	Beginning of DT&E to DSARC IIIB (months)	Beginning of IOT&E to DSARC IIIB (months)
A-10	35	35
F-15	7	7
F-16	10	- 9

sion, Fairchild had delivered 27 production A-10s, about 4 percent of the planned production buy of 733 aircraft.

Schedule Performance

The program began with exemplary schedule performance by both contractors during the Competitive Prototype Phase, with each contractor either meeting or beating all major scheduling milestones, as seen in Table A.14. The RFP for this program phase, issued in May 1970, provides the first meaningful insights about Air Force expectations of schedule performance for the AX program. Labeled as approximate in the RFP, the estimates not unexpectedly reflect optimism about the schedule performance in some areas. For example, the estimate in the RFP of Initial Operational Capability (IOC) could not anticipate the rampant inflation and contractor difficulties that reduced the buildup in production rates, hence the 41 percent error in estimating the time to achieve IOC.

The March 1973 schedule, coincident with the award of the full scale development contract to Fairchild, provides a detailed baseline from which we can measure the schedule performance of the program. That schedule called for the procurement of 10 DT&E aircraft and 729 production aircraft. The production aircraft delivery schedule in March 1973 included a peak-production rate of 20 aircraft per month, with the last delivery occurring in mid-1980. By comparing the March 1973 schedule with the current schedule in Fig. A.5, we can see the considerable effect of the change in production delivery schedule.[33]

The source of the schedule slippage can be attributed to (1) congressional actions, (2)

Table A.14

A-10 PROGRAM SCHEDULE PERFORMANCE RELATIVE TO ORIGINAL SCHEDULE IN COMPETITIVE PROTOTYPE PHASE RFP

Event	Planned (months)	Actual (months)	Schedule Slip (months)	Actual Time Divided By Planned Time
Competitive prototype phase contract award to -				
o Prototype aircraft first flight	18	17	-1	0.94
o Beginning of Air Force flight evaluation	22	22	0	1.0
o FSD DT&E aircraft first flight	48	50	2	1.04
o Initial operational capability	58	82	24	1.41

[33]After the contract award in March 1973, the A-10 program had nine different production schedules in four and one-half years.

voluntary Air Force schedule changes to stay within funding limits, and (3) OSD reductions in the planned maximum production rate and funding levels. Slippage began with a two-month delay in the contract award because of congressional interest in the source-selection decision. Although Fairchild accelerated efforts to meet the original schedule, the two-month delay in awarding the contract and late receipt of vendor items, tooling, and critical materials delayed the initial flight of the first FSD DT&E aircraft by six weeks. In FY 1974, Congress deleted four RDT&E aircraft,[34] disallowed $30 million of long lead production funding, and directed the YA-10/A-7D flyoff. This, together with congressional direction to procure fewer aircraft in FY 1975, ultimately caused a four-month delay in achieving IOC. The Air Force also extended IOT&E Phase I testing by 5.5 months to make up for test time lost because of

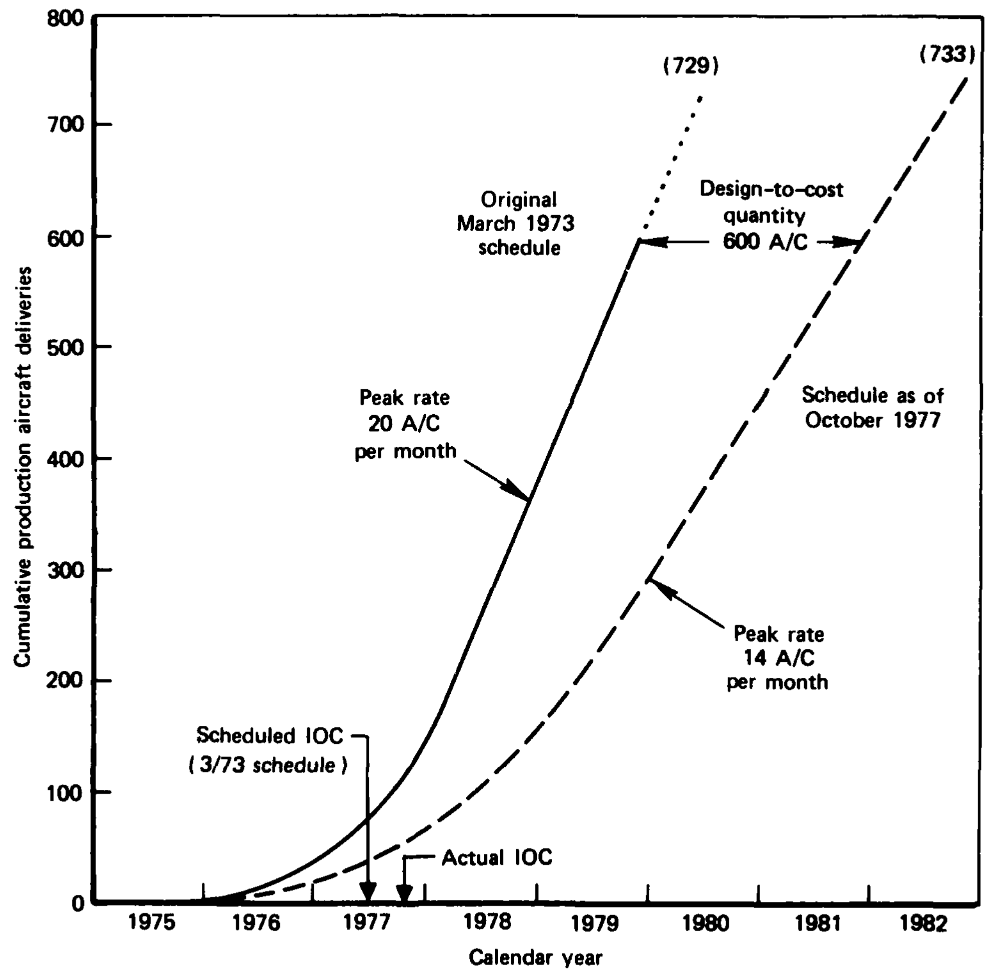


Fig. A.5—A-10 production schedules

[34]These four aircraft were later transferred to production to yield the 733 production aircraft figure shown in Fig. A.5.

the YA-10/A-7D flyoff, as well as to perform further gun integration and other system tests using the prototypes.

Beginning in mid-1973, the inflation rate began to increase substantially, contributing to both scheduling and cost problems. To stay within immediate funding limits, the Air Force voluntarily stretched production schedules by reducing procurement.[35] But the most significant change to the A-10 schedule came as a result of the DSARC IIIB deliberations that directed the Air Force to limit the peak-production rate to 15 aircraft per month rather than the original goal of 20, and to provide for a slower buildup to the peak-production rate. OSD justified the action by saying it would (1) provide greater confidence that the contractor could finance and manage the program without difficulty, (2) provide a slower buildup in production more consistent with the expected schedule for resolving reliability difficulties encountered in early flight testing,[36] and (3) be consistent with expected funding in FY 1977 and beyond. In July 1977, because of fiscal limitations, the Air Force recommended, and OSD subsequently approved, a decrease in the peak-production rate to 14 aircraft per month. These changes introduced a projected two-year delay in the delivery date of the 600th design-to-cost airplane and about a 27-month delay in the delivery date of the last aircraft. For the most part, these production delays in the A-10 program are not the type that a prototype program could foretell.

Overall, Table A.15 indicates that the A-10 program has generally met or come reasonably close to most of the milestones scheduled during development or early in production. The 3 percent slippage in the A-10's initial operational delivery is considerably smaller than the average 15 percent slippage that characterized weapon system developments of the 1960s and 1970s.[37]

PROGRAM COSTS

The AX/A-10 program, the first major weapon system to be developed under the Design-to-Cost (DTC) concept, had a strong cost focus from its inception. The analysis of AX/A-10 program costs that follows has three main objectives: (1) to tabulate the expenditures devoted to the AX competitive prototype phase and compare them with total program costs, (2) to determine whether the prototype phase enhanced the accuracy of the cost estimates for subsequent phases, and (3) to trace the evolution of the A-10 DTC goal and rate its success in restraining growth in that aircraft's flyaway cost.

Acquisition costs customarily are discussed in terms of base-year constant dollar values or in then-year (inflated) dollars. Costs expressed in then-year dollars are useful for indicating the budget levels that eventually will be needed to finance the programs, but that is not our objective here. Expressing cost growth in constant base-year dollars (approximating the year of DSARC II) emphasizes the "real" cost changes in the program, but lack of a common

[35]For example, the Air Force initially requested transition quarter (July-September 1976) funding for the delivery of 33 aircraft during the February to April 1978 time period. Congress subsequently cut the request to 30. Later, because of inflation, the Air Force cut the quantity to 20 to avoid a cost overrun. (Department of the Air Force response to questions submitted by Sen. Cannon, in U.S. Senate, *FY 1977 Authorization . . .*, March 12, 1976, p. 5139.)

[36]The contractor was required to demonstrate a 6.6-hour mean time between failures (MTBF) at the end of DT&E. AFFTC measured a 5.6-hour MTBF. Problem areas included the short life of main tires, unreliable brakes, etc. See Captain Jeffery F. Brown and Neal F. Chamblee, *A-10 DT&E Reliability . . .*, AFFTC-TR 76-35, September 1976, p. 141.

[37]See Robert L. Perry et al., *System Acquisition Strategies*, The Rand Corporation, R-733-PR/ARPA, June 1971, p. 7; and Edmund Dews et al., *Acquisition Policy Effectiveness: Department of Defense Experience in the 1970s*, The Rand Corporation, R-2516-DR&E, October 1979.

Table A.15

A-10 PROGRAM SCHEDULE PERFORMANCE RELATIVE TO FULL SCALE DEVELOPMENT CONTRACT SCHEDULE

Event	Planned (months)	Actual (months)	Schedule Slip (months)	Actual Time Divided By Planned Time
Full scale development contract award to -				
o FSD DT&E aircraft first flight	22	24	2	1.09
o Production aircraft first flight	32	32	0	1.0
o Initial operational delivery	35	36	1	1.03
o Initial operational capability	52	56	4	1.08
o Delivery 600th aircraft (projected)	82	106	24	1.29

denominator creates difficulty in making cross-comparisons with other programs having different base years. Also, costs expressed in FY 70 dollars are nearly meaningless today; the dollar in 1970 could buy twice as much as it can today. Use of constant present-year dollars avoids these problems and *reference to costs in the sections that follow will be in FY 81 dollars unless otherwise stated.* DoD deflators were used to compute the approximate FY 81 dollar equivalents.

Prototype Phase Costs

The Air Force spent the equivalent of $176 million (in FY 81 dollars) for the AX competitive prototype phase (see Table A.16), more than 80 percent of which went to the airframe and engine contractors. In addition to the government funding, Northrop reportedly spent approximately $16.5 million of its own funds during the competition, and unofficial estimates place Lycoming's investment at about $3 million.[38] We have no comparable information on company funding of the Fairchild/General Electric candidate system if, indeed, there was any.

The prototype phase did not add significantly to total program costs. As shown in Table A.17, The Air Force's investment for the prototype effort amounts to less than 2 percent of the total program costs in then-year dollars, or about 3 percent when expressed in constant dollars.

[38]These estimates are equivalent to $8 million for Northrop and $1 to $2 million for Lycoming in then-year dollars.

Table A.16

COSTS OF AX COMPETITIVE PROTOTYPE PHASE
($ millions)

Description	Base-Year $[a] (FY 70)	Present-Year $[a] (FY 81)	Then-Year $[b] (FY 70-73)
Air Vehicle	66.9	146 0	70.1
Fairchild/GE	(39.3)	(85.8)	(41.2)
Northrop/Lycoming	(27.6)	(60.2)	(28.9)
System test	10.8	23.5	11.7
Flyoff	1.2	2.7	1.4
Other	1.8	4.0	1.8
Total	80.7	176.2	85.0

[a]Distribution of costs by base-year dollars and then-year dollars presented in A-10 SAR, July 1977, p. 6. Equivalent FY 81 dollars estimated with raw DoD deflators.

[b]Distribution of then-year dollars by descriptive category furnished by the A-10 SPO. Corresponding figures in base-year dollars estimated with DoD deflators weighted by expenditure pattern.

Table A.17

A-10 TOTAL PROGRAM COSTS AS ESTIMATED IN SEPTEMBER 1980
($ millions)

Item	Base-Year $ (FY 70)		Present-Year $ (FY 81)		Then-Year $ (FY 70-84)	
	$	%	$	%	$	%
Prototype	$ 80.7	3.2	$ 176.2	3.2	$ 85.0	1.4
Other development	263.5	10.4	575.3	10.4	387.6	6.4
Procurement	2188.9	86.4	4779.3	86.4	5564.2	92.2
Total	$2533.1	100.0	$5530.8	100.0	$6036.8	100.0

SOURCES: Prototype cost: A-10 SAR, July 1977. Total FSD and Procurement: A-10 SAR, September 1980.

Cost Growth

In this section we will address the question of whether the existence of the AX prototype program with its actual hardware and cost data base enabled the estimators to improve the initial cost projections for the A-10 acquisition program. Table A.18 presents the baseline Development Estimate (DE) and the most recent cost growth projection that was available at the time of writing, drawn from the September 1980 Selected Acquisition Report. They are shown in that source in base-year (FY 70) dollars and then-year dollars, the latter including the effect of the expected future inflation rates on the required funds. We added the figures in the center column to show the costs in present-year (FY 81) dollars, the form we consider the most useful in the present analysis.

Table A.18 shows A-10 development, procurement, and total program costs. For each group, the baseline DE is shown, followed by the cost changes, which are distributed among the several descriptive "cost variance" categories used in the SAR system. The sum of the DE and total variance equals the Current Estimate (CE), as projected in September of 1980. All of the SAR variance cost categories, with the exception of Support, relate to changes in the *aircraft* costs. The Support figure is the sum of all of the cost changes, regardless of cause, in the original estimates for ground support equipment, training equipment, depot maintenance equipment and technical data. The Economic category appears in the "Then-Year $" column only. It accounts for unanticipated escalation—the shortfall in DoD's previous projections of future inflation rates.

Development Costs. With fixed-price contracts, the Air Force experienced no cost growth during the competitive prototype phase. The extent to which the contractor's investments were planned, or covered unanticipated cost growth, is unknown.

The cost growth shown for the A-10 development phase, 22 percent, is better than that of most of the nonprototype aircraft programs that were compared in Rand's earlier-cited R-2516-DR&E. Some of the A-10 cost increases resulted from policy changes that were made after the DE was established. For example, the engine Component Improvement Program (CIP) cost of $47 million and test center costs of $12 million do not represent additional costs (to the Air Force) since they previously were carried in other program element accounts. The congressionally directed flyoff between the A-10 and the A-7D that cost $3 million had nothing to do with A-10 development per se, but its cost also was added to A-10 development after the initial DE had been submitted.

Conversely, in FY 1976, the development cost total experienced a decrease of $31 million because of a decision to transfer four development aircraft to the procurement group, which obviously did not generate any *net* savings in an overall program sense.[39] If we omit the above plus and minus cost changes, the increase in the A-10 development cost becomes 17 percent. This latter increase stems primarily from additional tests ($14 million), enhanced avionics and follow-on development ($103 million), and test schedule slippage ($23 million). The slippage resulted from a congressional cut in the FY 1975 R&D appropriations, which forced rescheduling of a number of test events to a later time period. Costs rose because a large proportion of the expenses (wages, etc.) continued unabated during the delay. The Air Force included FY 1977 funds for the development of a two-seat trainer but then deleted them the following year (apparently after some preliminary work had been charged). Of these increases, $34 million were offset by some overestimates in the original DE.

---

[39]*In fact, having fewer R&D aircraft may have raised costs somewhat because of the need to reconfigure the available aircraft more often for the various tests.*

Table A.18

A-10 Program Acquisition Cost
($ millions)

Item	Base-Yr (FY 70) $ Cost	Base-Yr (FY 70) $ % of DE	FY 81 $ Cost	FY 81 $ % of DE	Then-Year $ Cost	Then-Year $ % of DE
Development (Quantities: DE =		14,	CE =	10)		
Development Estimate	281.9	100.0	615.5	100.0	336.7	100.0
Variance:						
Quantity	-14.4	-5.1	-31.4	-5.1	-18.9	-5.6
Schedule	10.6	3.8	23.1	3.8	15.1	4.5
Engineering	47.1	16.7	102.8	16.7	86.5	25.7
Estimating	-15.5	-5.5	-33.8	-5.5	-17.4	-5.2
Other	22.8	8.1	49.8	8.1	28.8	8.6
Support	11.7	4.2	25.5	4.2	18.3	5.4
Economic					23.5	7.0
Total variance	62.3	22.1	136.0	22.1	135.9	40.4
Current estimate	344.2	122.1	751.5	122.1	472.6	140.4
Procurement (Quantities: DE =		729,	CE =	825)		
Development Estimate	1486.5	100.0	3355.5	100.0	2153.0	100.0
Variance:						
Quantity	120.3	8.1	271.6	8.1	383.5	17.8
Schedule	467.6	31.5	1055.5	31.5	1422.3	66.1
Engineering	128.9	8.7	291.0	8.7	291.1	13.5
Estimating	-92.0	-6.2	-207.7	-6.2	8.4	.4
Other	.0	.0	.0	.0	.0	.0
Support	7[illegible]	5.2	175.2	5.2	215.7	10.0
Economic					1090.2	50.6
Total variance	702.4	47.3	1585.6	47.3	3411.2	158.4
Current estimate	2188.9	147.3	4941.1	147.3	5564.2	258.4
Total Program (Quantities: DE =		743,	CE =	835)		
Development Estimate	1768.4	100.0	3971.0	100.0	2489.7	100.0
Variance:						
Quantity	105.9	6.0	240.1	6.0	364.6	14.6
Schedule	478.2	27.0	1078.7	27.2	1437.4	57.7
Engineering	176.0	10.0	393.8	9.9	377.6	15.2
Estimating	-107.5	-6.1	-241.5	-6.1	-9.0	-.4
Other	22.8	1.3	49.8	1.3	28.8	1.2
Support	89.3	5.0	200.7	5.1	234.0	9.4
Economic					1113.7	44.7
Total variance	764.7	43.2	1721.6	43.4	3547.1	142.5
Current estimate	2533.1	143.2	5692.6	143.4	6036.8	242.5

SOURCE: September 1980 SAR.

Although A-10 development cost growth is below average for development in the 1970s, it can be argued that the accuracy of these projections is overstated because the baseline DE includes prototype program costs that had already been incurred. These prototype costs may properly be considered development costs, but they obviously should be excluded when we are evaluating whether accuracy in predicting future program costs is improved by a prior prototyping effort. Exclusion of the prototype costs ($169 million) yields a revised DE (limited to FSD) of $446 million. The $136 million increase shown in Table A.18 then is equivalent to 30 percent cost growth. Using the alternative accounting scheme (excluding CIP costs, the A-7D/A-10 flyoff costs, etc.) results in an adjusted "real" cost growth of about 25 percent. Although these adjustments raise A-10 development cost growth somewhat, its experience is still better than the median development cost growth noted in other contemporary acquisitions. Because the development costs constitute only 13 percent of total A-10 program costs, these adjustments have no noticeable effect when viewed in the total program context.

Procurement Cost Growth. Table A.18 indicates that A-10 procurement costs have grown by 47 percent in real terms when measured against the baseline DE of $3356 million. By far the greatest contributor to this increase has been schedule slippage, which added more than $1 billion to A-10 acquisition costs. The OSD decision to reduce the maximum production rate from 20 to 15 aircraft per month is charged with $617 million of this schedule slippage cost growth. This rate cut and other schedule delays account for two-thirds of A-10 production cost growth.

The second largest cause for procurement cost growth is the engineering changes since DSARC II. The main contributor in this category was the upgrading of the avionics, expanded considerably beyond the original rather austere configuration. A notable example is the addition of an inertial navigation system (INS) which added approximately $250,000 to the cost of each aircraft. The total engineering variance would have been greater than that shown in the table if the change had been approved sooner, but half of the A-10s had been built before the INS could be introduced on the production line and, as a consequence, the cost of adding the INS to more than 400 A-10s is excluded from these cost growth figures. This avionics system, as well as the other "update modifications" that had to be retrofitted into already-produced aircraft, are funded in a separate budget, Modification of In-service Aircraft, the costs of which are not covered by the SAR system. Although the addition of these post-production costs would have increased the A-10 cost growth by 6 to 7 percentage points, this situation is not unique to the A-10 program. Most, if not all, of the military acquisition programs have modifications that are not accounted for in the cost growth statistics. For the limited purposes of this study, completeness must give way to consistency.[40]

Eight percentage points of the A-10 procurement cost growth are attributed to the 96-aircraft increase in total quantity. Four of these aircraft were simply transferred from the development budget to the procurement budget at the urging of Congress and are matched by an equal reduction in the development cost group. The other 92 were added to the buy in FY 1980. Total procurement costs are, of course, very sensitive to the number of units produced, and it would be misleading to compare cost growth ratios of several different programs if some held production quantities constant while others did not. For this reason, we have attempted to normalize all of the cost growth figures in this study to correspond with the original baseline quantities that underlie their original cost estimates.

---

[40]The possibility that the incidence of modification costs for individual programs may not be proportional to their SAR variance totals must be kept in mind when one compares programs whose cost growth percentages are not grossly different. An analogous situation has developed in the area of flight simulators. There is a growing tendency to delay their procurement to the post-production years. In so doing, the cost of these simulators bypasses the SAR cost growth tracking system.

A rough correction for quantity-induced cost growth could be made by simply deleting the Quantity variance. However, Quantity variance accounts only for the expenditures attributed to the additional *aircraft*. The corresponding increase in the cost of associated ground support equipment also should be deleted. This latter cost increase is included in the aggregative Support variance category, following the SAR guidelines, but, fortunately, the A-10 SPO broke out these support equipment add-on costs in the December 1979 SAR as a part of its detailed explanation of the costs incurred by the quantity increase. Besides the above costs generated by the quantity increase per se, any cost growth subsequent to the change is in terms of the new aircraft quantity, and it should be adjusted to represent the baseline quantity.

Table A.19 demonstrates the method used to normalize procurement cost growth to the smaller baseline quantity. The figures are displayed in both FY 70 (base year) and FY 81 dollars. Because of the interest in aircraft flyaway cost growth in relation to the A-10 DTC goal, the adjustment of these costs is shown separate from the other (support) variance. Procurement cost growth was summed separately for two time periods representing different A-10 total quantities—733 and 825. These sums were scaled down proportionally to the 729-aircraft baseline quantity.[41] The costs attributed to the actual increases in aircraft quantities were, of course, omitted. This approach is intended to account for the total procurement cost growth over the entire program, whatever its eventual size; it does not ignore the cost of changes that occur after the output passes the original baseline quantity. On this basis, normalized procurement cost growth (as of September 1980) amounted to about 28 percent over the original estimate. This performance is not significantly better than that of the aircraft programs that were not preceded by a prototype competition.

DTC and Flyaway Cost Growth[42]

The CE normalized average flyaway cost per aircraft, $2.2 million, shown in Table A.19, does not relate directly to the DTC goals. The quantity is different from the recently revised goal, and compared with the original cost goals established for the A-10 program (there were two) the rate of production also is different. A brief digression to trace the evolution of the A-10 DTC will help to clarify this situation.

In the *Statement of Work* for the 1967 AX contractor-design studies, the Air Force established an average recurring flyaway cost goal ranging from $940,000 to $1.39 million for a production quantity of 1000 aircraft. The aircraft concepts developed in the contractor studies completed in September of that year generally fell within the cost guidelines. In 1968, the Air Force reduced the AX proposed buy to 600 and set the flyaway cost goal at $1.35 million. After further refinements, this was increased in the 1970 AX RFP to $1.4 million where it remained throughout the Competitive Prototype Phase. In its FSD proposal cost estimate, shown in Table A.20, Fairchild indicated that its design would meet the goal, but Fairchild's estimate of avionics equipment accounted for only 7 percent of the total. Following an OSD directive, the Air Force subsequently added another $100,000 for prorated nonrecurring costs, to arrive at the average flyaway cost goal of $1.5 million, which became the Air Force's DTC recommendation for the A-10.

---

[41]Use of learning curves would have made no significant difference in these adjustments.

[42]Because DTC goals are expressed in constant base-year dollars, this discussion will be conducted in terms of FY 70 dollars.

Table A.19

A-10 PROCUREMENT COST GROWTH, NORMALIZED FOR BASELINE QUANTITY
($ millions)

Estimates	Total Program			Normalized for 729 Aircraft				% of DE
	No.	Total Cost (FY 70 $)	$/Aircraft (FY 70 $)	Total Cost (FY 70 $)	$/Aircraft (FY 70 $)	Total Cost (FY 81 $)	$/Aircraft (FY 81 $)	
Total development estimate	729	1486.5	2.039	1486.5	2.039	3355.5	4.603	(100.0)
Flyaway								
Development estimate	729	1206.5	1.655	1206.5	1.655	2723.5	3.736	100.0
Variance								
Transfer from development	+4	14.4						
Before FY 80 incr	733	421.6		419.3	0.575	946.5	1.298	
Quantity increase	+92	236.7[a]						
Subsequent	825	-47.9		-42.3	-0.058	-95.5	-0.131	
Adj ("Support")	825	22.9[b]		20.2	0.028	45.6	0.063	
Total variance		647.7		397.2	0.545	896.6	1.230	32.9
Current estimate	825	1854.2	2.248	1603.7	2.200	3620.1	4.966	132.9
Other								
Development estimate	729	280.0	0.384	280.0	0.384	632.1	0.867	100.0
Variance								
Before FY 80								
Increase	733	22.3		22.2		50.1	0.069	
Quantity increase	+92	42.3						
Subsequent	825	13.0		11.5		26.0	0.036	
Adj (less "aircraft")	825	-22.9[b]		-20.2		-45.6	-0.063	
Total variance		54.7		13.5	0.019	30.5	0.042	4.8
Current estimate	825	334.7		293.5	0.403	662.5	0.909	104.8
Total variance	+96	702.4	0.614	410.7	0.563	927.1	1.272	(27.6)
Total current estimate	825	2188.9	2.653	1897.2	2.603	4282.6	5.875	(127.6)

NOTE: Figures rounded after calculations.
SOURCE: A-10 SARs, Various dates--most recent was September 1980.
[a]Quantity variance (using baseline cost curve) = $105.9 million; Schedule component = $111.9 million; Engineering component = $18.9 million. A-10 SAR, December 1979, p. 12.
[b]Adjustment needed to equal distribution of "Flyaway" and other A-10 acquisition cost changes. A-10 SAR, September 1980.

Table A.20

FAIRCHILD'S A-10 FULL SCALE DEVELOPMENT PROPOSAL
ESTIMATE OF RECURRING FLYAWAY COSTS
(Thousands of FY 70 $)

Component	Cost	Percent
Contractor-furnished equipment		
Airframe		
Labor	354.2	25.3
Raw material	66.1	4.7
Equipment	221.8	15.8
Subcontracts	101.5	7.2
Avionics	61.5	4.4
Total CFE	805.1	57.4
Government-furnished equipment		
Avionics		2.7
Gun		6.1
Engine		30.6
Other		3.2
Total GFE	598.7	42.6
Grand total	1403.8	100.0

SOURCE: Derived from Peter W. Odgers, Design-to-Cost . . ., Air War College, Report No. 5470, April 1974, p. 17.

After reviewing contractor data, prototype program results, and the costs of other tactical aircraft and interviewing Fairchild personnel, the CAIG concluded that the $1.5 million Air Force goal was too low, and recommended increasing the average flyaway cost goal to $1.7 million.[43] With the Air Force arguing to retain the $1.5 million goal, Deputy Secretary of Defense Clements devised a compromise:

> To break the impasse [he] directed that Department of Defense planning documents (Selected Acquisition Reports, Five-Year Defense Plans, etc.) would reflect estimates based on a $1.7 million (FY 70) cost target adjusted for quantity and escalation. In addition, Selected Acquisition Reports would state that Air Force management objectives were to procure A-10 aircraft at $1.5 million (FY 70).[44]

In other words, the lower Air Force DTC figure would act as a goal to keep the price down but financial planning would be based on the higher CAIG estimate. The disagreement proved to be academic in short order; both goals were soon overrun as financial problems induced by a number of factors led to schedule slippage.

[43]U.S. Congress, House Committee on Appropriations, Subcommittee on DoD, *DoD Appropriations for 1975* . . ., Hearings, 93d Cong., 2d Sess., Part 7, p. 1059.

[44]U.S. Congress, House Committee on Armed Services, Department of Defense Authorization for Appropriations for Fiscal Year 1978, Part 2, *Pro urement of Aircraft* . . ., Hearings, 95th Cong., February 13, 1977, p. 443.

An average flyaway DTC cost goal is always accompanied by a specification of the base-year dollars, production quantity, and peak-production rate.[45] The original DTC goal of $1.5 million was based on FY 70 dollars, 600 aircraft, and a peak-production rate of 20 aircraft per month.[46] The Air Force subsequently raised the DTC goal to $1.8 million to reflect the effect of reducing peak-production rates from 20 to 15 per month but retained the 600-aircraft output measure, a quantity whose cost cannot be tracked directly with SAR data. However, if we plot the current flyaway cost on an 80 percent learning curve, which is typical of tactical fighter aircraft, the average cost shown for the A-10 at a quantity of 600 units is approximately $2.2 million, the figure derived by the A-10 SPO. This represents a cost growth of 22 percent above the revised DTC goal of $1.8 million, and 29 percent above the CAIG estimate made when the A-10 program entered FSD.

Cost Summary (FY 81 $)

Table A.21 summarizes the A-10 development, procurement, and total program normalized cost growth. The total (unnormalized) program costs are shown as well, for reference. On the basis of the figures in the SAR, both the development and procurement phases witnessed roughly equal cost growth, 27 percent and 28 percent, respectively. If the costs of the prototype competitive program are omitted, in recognition that these costs were already known at the time of the DE cost projection, the accuracy of the cost growth projection is as shown in the columns to the extreme right: Development costs rise another 11 percentage points to 38 percent. Total program variance, however, is raised by only one percentage point to 29 percent.

The A-10 record lends little support to the belief that acquisition program cost growth may be greatly reduced by having prototype hardware and data upon which to base the DE baseline cost estimates. Inasmuch as two-thirds of A-10 cost growth resulted from schedule slippage that obviously could not be predicted with or without a prototype program, this end result should not be surprising. Although one might expect the prototype program and the DTC goal to restrain cost growth caused by engineering changes, the major add-on, an inertial navigation system, was not addressed in the prototype competition and the DTC goal was based on a minimal avionics component. The DTC goal is known to have been successful in warding off a number of less necessary performance enhancements, however, in the interest of keeping the cost close to the goal. With regard to Estimating variance, initial overestimates reduced by six percentage points the net cost growth of this program. If we disregard the direction of the estimating error, the A-10 Estimating variance, in absolute terms, is no better than average for aircraft acquisition.

[45]Note that only the peak rate was specified in the DTC goal although the average cost per aircraft used in the comparison would be influenced rather significantly by when this rate was reached and whether the acceleration to the peak rate was achieved with an orderly, sustained buildup of the labor force and material acquisition rate.

[46]A-10 SAR, September 1980, p. 7.

Table A.21

A-10 Program Cost Growth, Normalized for Baseline Quantity

($ millions)

Item	Total Program[a]			Normalized for 743 Aircraft						Normalized Cost Less Prototype	
	No.	Total Cost (FY 70 $)	$/Aircraft (FY 70 $)	No.	Total Cost (FY 70 $)	$/Aircraft (FY 70 $)	Total Cost (FY 81 $)	$/Aircraft (FY 81 $)	% of DE	FY 81 $	% of DE
Development											
DE	14	281.9		14	281.9		615.5		100.0	446.3	100.0
Variance		62.3			76.7		167.5		27.2	167.5	37.5
CE	10	344.2		14	358.6		783.0		127.2	613.8	137.5
Procurement											
DE	729	1486.2	2.039	729	1486.5	2.039	3355.5	4.603	100.0	3355.5	100.0
Variance		702.4		729	410.3	0.563	927.1	1.272	27.6	927.1	27.6
CE	825	2188.9	2.653	729	1897.2	2.602	4282.6	5.875	127.6	4282.6	127.6
Total Program											
DE	743	1768.4	2.380	743	1768.4	2.380	3971.0	5.345	100.0	3801.8	100.0
Variance		764.7		743	487.4	0.656	1094.6	1.473	27.6	1094.6	28.8
CE	835	2533.1	3.034	743	2255.8	3.036	5065.6	6.818	127.6	4896.4	128.8

[a]A-10 SAR, September 1980.

Appendix B

THE LIGHTWEIGHT FIGHTER PROTOTYPE PROGRAM

ANTECEDENTS OF THE LIGHTWEIGHT FIGHTER PROGRAM

The decision to develop a lightweight fighter aircraft, optimized for the air-to-air role, contrasted sharply with recent Air Force development decisions. In response to the primacy of the Massive Retaliation strategy and the dominance within the Air Force of the Strategic Air Command, tactical air warfare doctrine underwent a transition during the 1950s, resulting in major emphasis being placed on delivery of nuclear weapons. Although the McNamara administration of the early 1960s emphasized conventional warfighting capability, the notion that tactical aircraft should perform multiple missions prevented development of an aircraft devoted solely to dogfighting. Rapidly advancing air-to-air missile technology further contributed to the belief that the air-to-air combat role could be satisfactorily performed by aircraft that were sturdy radar and missile platforms and that would not engage enemy aircraft at close ranges where small size and maneuverability become important attributes.[1]

Attention to the air-to-air phase of the counterair mission increased in the mid-1960s as the Air Force initiated development of the F-X, an aircraft then aimed explicitly at the air-to-air mission. During concept formulation of the F-X, a debate developed over whether the aircraft should emphasize close-in maneuvering air-to-air combat capability or standoff missile attack. One school of thought argued that the close range combat of Korea and Vietnam was unlikely in the future, and that the typical scenario in a European war environment w[illegible] involve beyond-visual-range combat. TAC's air superiority fighter should therefore have sophisticated radar and missile avionics capabilities. Another view dismissed the likelihood of beyond-visual-range combat scenarios and doubted the abilities of even very sophisticated aircraft to destroy enemy fighters in such encounters. A key element in the later argument was the longstanding problem of accurately distinguishing between friend and foe by any means other than visual identification. The disappointing performance of long-range radar-guided air-to-air missiles in Vietnam strengthened that argument.

This debate was aided by the growing acceptance of the "energy maneuverability" theory of air-to-air maneuvering engagements, which provided a quantitative, analytical foundation for specifying the design and performance characteristics required to out-maneuver the threat aircraft. This helped lightweight fighter advocates to argue that good dogfighting qualities would not "fall out" of large complex aircraft designed for the beyond-visual-range role; instead, the tactical air forces should consist in part of lightweight, fairly inexpensive, dogfighting aircraft. One vehicle for expression of this viewpoint was a hypothetical design, promoted by the Office of the Assistant Secretary of Defense (Systems Analysis), known as the F-XX. Two contractors, General Dynamics and Northrop, created detailed designs. Each

[1]These themes are developed in Robert F. Coulam, *Illusions of Choice: The F-111 and the Problem of Weapons Acquisition Reform*, Princeton University Press, 1977; and Richard G. Head, *Decisionmaking in the A-7 Attack Aircraft Program*, Ph.D. Dissertation, Syracuse University, 1970.

aircraft, expected to weigh about 25,000 pounds, promised significant cost and performance improvements over the F-4 Phantom.[2]

The final decision on the F-X was a compromise, combining good maneuvering performance with a substantial radar missile capability. The resulting aircraft, the F-15 Eagle,[3] has a full internal weight of 40,000 lb (the initial F-X Development Concept Paper had called for an aircraft weighing 60,000 lb and costing considerably more than desired by the lightweight fighter advocates). Thus, development of the F-15 did not resolve the debate, and advocacy of lightweight fighters was continued.

In the spring of 1970, lightweight fighter proponents persuaded AFSC to fund small studies by industry and its own Aeronautical Systems Division (ASD). Northrop was awarded a contract worth $100,000, and General Dynamics, which also investigated a supercritical wing and the use of composite materials, received $150,000. The work statement for the studies was mission oriented and emphasized transonic and lower supersonic maneuvering. Those studies contributed to the establishment of the good technical foundation that subsequent events would require.

Soon after, unsolicited industry proposals began surfacing. The first was from Lockheed's Advanced Development Projects Division, known as the Skunk Works. In December 1970, Clarence L. "Kelly" Johnson, then head of the Skunk Works, told Secretary of the Air Force Robert Seamans (in a four-page proposal) that he could develop two prototypes of a lightweight fighter called the CL-1200 Lancer for a cost of $35-36 million, with first flight in 12 months. Seamans had publicly expressed concern over whether the Air Force could afford to buy the expensive F-15 in sufficient quantities[4] and commended the offer to Deputy Secretary Packard. A similar proposal by Northrop, based on the P-530 Cobra design that they had developed for export, was also submitted around this time.

That several-year period of studies and unsolicited proposals played a critical role in the evolution of the LWF prototype program by providing an extensive body of information for use in developing system requirements. Therefore, when the call went out for candidate systems, the LWF advocates were ready with a concept that was well developed in both technical and operational terms and that had the backing of key personnel at many levels of the Department of Defense. The necessary homework had been thoroughly done.

When Deputy Secretary Packard proposed his prototyping program to Congress in the fall of 1971,[5] requesting $67.5 million in FY 1972, the LWF was among the 12 items included in the package. Packard told Congress that the Department of Defense was

> interested in pursuing a lightweight fighter, principally to demonstrate technology, high maneuverability, and good controllability throughout the performance range of the aircraft. There have been a number of advances in [these areas]. We would like to take a specific aircraft design and demonstrate it. Because of the technical risks involved in some of these particular

---

[2]See Jack N. Merrit and Pierre M. Sprey, *Negative Marginal Returns in Weapons Acquisition*, in Richard G. Head and Ervin J. Rokke (eds.), *American Defense Policy* (3rd ed.), Johns Hopkins Press, Baltimore, 1973, pp. 486-495; U.S. Senate Committee on Armed Services, *Weapons Acquisition Process*, Hearings, 92d Cong., 1st Sess., 1971, pp. 239-289, esp. pp. 244-246, 254-256 (testimony of Pierre M. Sprey).

[3]McDonnell Douglas was chosen to develop and produce the F-15 Eagle on 24 December 1969. The other competitors were Fairchild Hiller and a team from North American and Northrop. McDonnell Douglas was almost persuaded by lightweight fighter proponents to submit an alternative design, called "Redbird," as well. It would have been smaller and cheaper than the F-15.

[4]"The F-15 is a program that is very near and dear to us right now. It has been well thought through and there is every indication that this plane will be a substantial improvement over the F-4 and F-111. However, in view of mounting labor, management and material costs, the question is, can we buy enough of them?" *Armed Forces Management*, October 1969.

[5]U.S. Senate, Committee on Armed Services, *Advanced Prototype*, Hearings, 92d Cong., 1st Sess.; U.S. House of Representatives, Committee on Armed Services, *Use of Prototypes in the Development and Procurement of Weapon Systems*, Hearings, 92d Cong., 1st Sess.

features, we have not been able to include an optimum combination of these design ideas in our approved development program.[6]

The areas of technical risks he spoke of included technological advances in high acceleration cockpits, sidestick/fly-by-wire control, automatic variable camber, neutral stability, and the flutter, lift, and drag problems associated with high aspect ratio thin wings. The Air Force hoped eventually to use the program to investigate other challenging areas: composite structures; side force, direct lift, and task-oriented control; and integrated stores.[7] And, of course, the value of a small, lightweight air-to-air fighter with exceptional maneuverability but austere avionics was itself a critical uncertainty.

The Air Force Prototype Study Team, acknowledging the large number of contractors that expressed interest, recommended a dual-source prototype program in which the design and performance objectives would be stated as goals, not rigid requirements; design tradeoffs would thereby be encouraged. Ten such goals were suggested for the LWF:

- Gross weight less than 20,000 lb
- Unequalled performance and maneuverability in the transonic high-g arena
- Combat radii of 225 n mi (internal tanks) to 700 n mi (with external tanks)
- Mach 1-1.2 at sea level and Mach 2 at altitude (with fixed geometry inlets)
- In-being or late development propulsion
- Mission-essential avionics
- Representative state-of-the-art high muzzle velocity gun and effective, low-cost air-to-air missile
- Hardpoints and systems for credible air-to-ground capability
- Excellent pilot visibility
- Excellent handling qualities

The aircraft (two from each contractor) would be tested jointly by the contractor and the Air Force for about 300 hours each. This time would be evenly divided for contractor, performance, and operational testing. The entire activity was expected to cost $90 million.[8]

MANAGEMENT OF THE PROTOTYPE PROGRAM

As recommended by most prototyping proponents at the time, the Air Force acknowledged that successful prototyping required unusual management practices—in Air Force parlance, "Adaptive Management."[9] The Prototype Study Team formulated five major principles for managing the prototype programs:

- Use small government and industry organizations. The Air Force Program Manager should have maximum responsibility for program decisions.
- Use contractor-formatted data, when data are required, to avoid reformatting costs.
- Minimize controls and program documentation within both industry and govern-

[6] *Advanced Prototype*, Hearings, pp. 17-18.
[7] *Final Report, USAF Prototype Study*, App. 4, pp. 13-14.
[8] This was the figure Packard gave to the Congress. The Air Force Prototype Study Team expected the total cost to be $70 million.
[9] This argument was reemphasized when the program moved to FSD and both the SPO and the contractor were forced to rapidly evolve to a different management to cope with the details of a large-scale production-oriented program.

ment. Emphasize on-site assessment in lieu of contractor documentation.[10] Waive many regulations such as Production Plan (AFSCM84-3), Integrated Logistics Support Plan (AFSCR/AFLCR 400-10), Value Engineering (AFR 70-16). Encourage the contractor to simplify his own management techniques.

- Defer both managerial and technical elements not directly related to the prototype program. Such elements include configuration management, supporting technical data, and reprocurement data.
- Tailor testing to attainment of specific program goals. Category I, II, and III testing, required by AFR 80-14, should not be conducted. Rather, the contractor and the Air Force should jointly perform both the air worthiness demonstration and the flight evaluation, with the Air Force entering the program at the earliest possible date.

Responsibility within the Air Force for the prototype programs was to reside in a special Advanced Prototype Programs Office in the Aeronautical Systems Division of Air Force Systems Command.

Although the plans did not officially include production, LWF proponents generally supported the decision to prototype the LWF competitively. Competition for limited Air Force RDT&E funds would be avoided because Packard proposed to fund the prototypes separately and not from the Services' budgets. Criticism about sole-source contract awards would likewise be avoided and the industry-wide solicitation would insure that the best proposals would be considered. This freedom from formal force structure planning had significant benefits in the form of independence from schedule pressures, institutionalized goals and milestones, elaborate contractual instruments, etc.

Two points must be kept in mind, however. First, regardless of the official plan, all the candidate contractors and those in the Air Force directly involved in the various LWF efforts consistently acted as if an LWF would in fact be produced.[11] Second, the effects of the LWF's exclusion from formal force structure planning were not all positive. As an example, neither an operations concept nor a support concept was available when prototype development started, and the SPO had to improvise on all decisions relating to those areas. The extent of air-to-ground capability to be built into the design was a particularly troublesome issue, and one that would normally have been strongly influenced by the operating command. Such lack of guidance turned out to be a source of some problems when the project moved into FSD on a tight schedule. If an operations and support concept had been defined before, or even during, the prototype phase, the contractors could have been doing maintenance- and support-related design refinement studies during the flight-test phase in anticipation of FSD. The cost would have been small, and the benefits quite large. As it was, important decisions about the LWF's operational mission and maintenance concept were not made until the late stages of the prototype program. TAC did not begin to study mission-related issues seriously until the spring of 1974. AFLC did provide limited participation in early SPO planning efforts.

---

[10]The Air Force Prototype Study Team even suggested that the Air Force Program Office could perhaps be collocated with the contractor's design and engineering facilities.

[11](The) "aircraft was first configured in an operational form and then departures were made in details to meet the specific objectives of costs and schedules required by the two-airframe prototype concept." William C. Deitz, *Preliminary Design Aspects of Design to Cost for the YF-16 Prototype Fighter*, presented at the AGARD Flight Mechanics Panel Symposium, Florence, Italy, October 1973.

Selection of the Contractors

The RFP for the Lightweight Fighter was issued on 6 January 1972. The document drew on inputs from several industry and Air Force sources. In contrast to the documents issued for developments in the past, the main substance of the RFP (the statement of work, source-selection criteria, etc.) was only 10 pages, and the total was only 54 pages (including legal boilerplate) instead of the usual several hundred pages.[12] Moreover, contractor responses were explicitly limited to 50 pages of technical information and 10 pages of management data. In the past, such documents had often exceeded 2000 pages. The recipients were told:

> The objective of this procurement is to provide prototype hardware for Air Force test and evaluation of design, technology, and military usefulness in support of anticipated military needs. The Program will not replace the current equipment/systems acquisition cycle but should assist in reducing the cost, time, and technical risks associated with the development phase of that cycle. Among the key features or characteristics of the Advanced Prototype Program are new or renewed emphasis on simplified and streamlined management and procurement approaches, minimal documentation and reporting and establishment of design goals rather than specifications.

The RFP indicated that funds for the total program would not exceed $90 million inclusive of GFE/GFAE and contractor and Government Base Support.

The Statement of Work included in the RFP was contained on one page. It required the contractor to design, develop, and fabricate two prototypes; certify the flight safety of each aircraft throughout its envelope; conduct a flight-test program to verify the satisfaction of the "performance/design requirements"; train four Air Force pilots; provide logistics, engineering, and maintenance support during the approximately 12 months of testing (hours to be specified by the contractor); provide certain data; and prepare and submit a final report, including recommendations for follow-on engineering development.

The RFP allowed six weeks for submission of proposals. By the 18 February 1972 deadline, five companies had responded: Boeing, General Dynamics, Lockheed, Northrop, and Vought (then LTV Aerospace). On 14 April 1972, the Air Force announced General Dynamics and Northrop as winners.

As a part of the prototype proposals submitted in February 1972, the five bidding companies were asked to submit wind tunnel models of their proposed LWF design configurations. Air Force engineers tested these models in the NASA Ames test facilities in a very rapid (albeit limited) schedule, and the data were processed as part of the source-selection evaluation. Members of the source-selection team thought the test results were a valuable evaluation input yielding improved confidence in the predictions of aerodynamic characteristics.

Contract Philosophy

The ceiling of $90 million on total prototype program cost was exceeded. General Dynamics was awarded a $37.9 million contract; three F100 engines were provided to General Dynamics at a cost to the government of about $7 million. Northrop received a $39.1 million contract; the Air Force also awarded General Electric $20 million, half of which represented about half the expected cost of further development of the J101 engine and the other half of

[12] *Advanced Prototype*, Hearings, pp. 21, 45.

which was used to provide seven engines for use by Northrop.[13] The Air Force outlay to the four contractors was therefore about $105 million, and additional expenses totaled nearly $8 million. The major contractors almost certainly contributed additional funds of their own. Further details on program cost are presented later in this appendix.

Among the most prominent management innovations in the program were the prototype contracts. They were significant in three respects. First, they explicitly waived Military Specification requirements. The practical effect of this was not so much that MilSpec standards were not met—both contractors tended to abide by MilSpecs as a matter of course—but rather that the sometimes extensive compliance documentation was avoided. Second, unlike the fixed-price contracts signed with Northrop and Fairchild for development of the AX prot types, the LWF contracts were cost-reimbursement contracts with a ceiling on the gover ment's obligation. This provided the Air Force with two benefits. First, one of the pri advantages of a cost contract—access to the contractor's books—was attained without sac ficing a fixed-price environment. This helped the Air Force to better determine the real c of the prototype phase, not just the *price*. Second, a Limitation of Government's Obligati (LOGO) clause permitted the establishment of yearly funding limits, a practice that great enhances budgetary control but is not ordinarily allowed with cost-reimbursement contracts.

This type of arrangement has been used in other Air Force programs—the F-15, B-1, and AWACS, for example. Application in this situation, however, contravened accepted practice. The Commission on Government Procurement wrote:

> The [LOGO] clause is deceptively simple but requires great managerial skill to apply. It requires that detailed program financial planning be done far in advance of the work itself. The clause has greater application to a long-term commitment made to one system when the uncertainties of cost, performance, and schedule dictate use of a cost-type contract. The clause would not be appropriate, for example, to competitive system contracts that limit development work to prototype demonstration and specify the amount that each contractor can recover from the demonstration effort.[14]

Despite this guidance, the clause was successfully used, partly because the ceilings, while "tight," were not unrealistic (suggesting successful planning) and partly because the potential for very lucrative follow-on work sharpened the efforts of the competitors. At least one contractor did contribute some corporate resources, but Air Force funding was apparently adequate to complete the program; and any corporate funds represented a deliberate investment to improve the chances of winning any subsequent development and production contracts.

Finally, although the Statement of Work was premised on the fabrication of two flyable aircraft, the contractor was obligated only to use his "best effort" to achieve the program goals. In fact, the Air Force told the bidders that they could fulfill their contractual obligation by "delivering a flatbed of bolts" if that represented their best effort using the contractual amount. However, although cost-sharing was thereby implicitly ruled out (except in the GE contract), the competitive environment insured that the Statement of Work tasks would be the real goals (not "best effort"), to which corporate funds would be committed if necessary. The importance in this arrangement of the potential for follow-on work cannot be underestimated. That is, if the program had clearly provided no expectation of follow-on business, the

---

[13] The YF-16 had one engine, and the YF-17 had twin engines. Thus each airframe contractor was provided one spare ship set of engines. Because of the relative immaturity of the J101 at that time, one extra engine was provided to Northrop.

[14] *Report of the Commission on Government Procurement*, Vol. 2, p. 168.

contractors would have had little motivation to devote so much of their talent and money, even in a dual-source competitive environment.

SPO Management

Management of the LWF and AMST programs was originally consolidated in the Prototype Program Office, which was formed within ASD on 27 August 1971. The director of the office (originally Col. Lyle W. Cameron, who was replaced by Col. William E. Thurman in June 1973) reported first to ASD Deputy for Systems, then later directly to the Commander of ASD. A separate System Program Office (SPO) was not established for the LWF program until October 1974, several months after the decision was made to proceed with full scale development.

The number of Program Office personnel assigned to the LWF program was remarkably low throughout the prototype period, particularly compared with other, more conventional programs. As late as January 1974, there were only four full-time personnel. During the flight-test programs, the office never exceeded 50 or 60 people, exclusive of representatives from Europe. After the selection of the F-16 and the start of full scale development, the manning level grew rapidly (see Fig. B.1) despite reported attempts to enforce a 125-man limit. Many SPO personnel from that early period believe that manning levels were "too tight," especially that manning was not increased fast enough when the program evolved rather quickly from an austere prototype program to a complicated, multi-national FSD program.

As planned, communication with the contractors was primarily on an informal, one-to-one (often in person) basis during prototype development. This was true for both financial and engineering matters. Formal reporting requirements were minimal, although each contractor chose to submit monthly reports. This was possible in part because of the goal-oriented, specification-lacking program documents and in part because of the austere SPO manning policy adhered to throughout the prototype phase. In addition, ASD instructed the Air Force Plant Representative Offices (AFPROs) at Northrop and General Dynamics to limit their involvement in the prototype phase to safety and quality control issues. Another practice reducing management workload and facilitating tight scheduling was that design reviews were conducted incrementally, involving only the technical and management personnel responsible for that portion of the design.

One factor that helped make austere manning practical was the almost complete absence of reliability and maintainability (R&M) planning for the prototype vehicle. As originally conceived, the prototype program had little need for R&M planning because the vehicles were only for demonstration of design concepts, not pre-production items. However, R&M was not completely ignored. An AFLC officer was assigned to the Prototype Program Office in May 1972. During the remainder of that year his duties were largely limited to assisting the contractors in selecting off-the-shelf subsystems and components that would contribute to good R&M characteristics in the prototype vehicles. He also participated in the design of flight-test data collection efforts so that R&M-related design deficiencies would be identified and documented. The test design work was supported by a LWF Development Concept Paper draft issued in September 1972, which identified R&M evaluation as an objective of the LWF test program.

In late 1973 and early 1974, as the possibility of turning the LWF prototype into a weapon system grew stronger, the interest in R&M planning became more pronounced. The

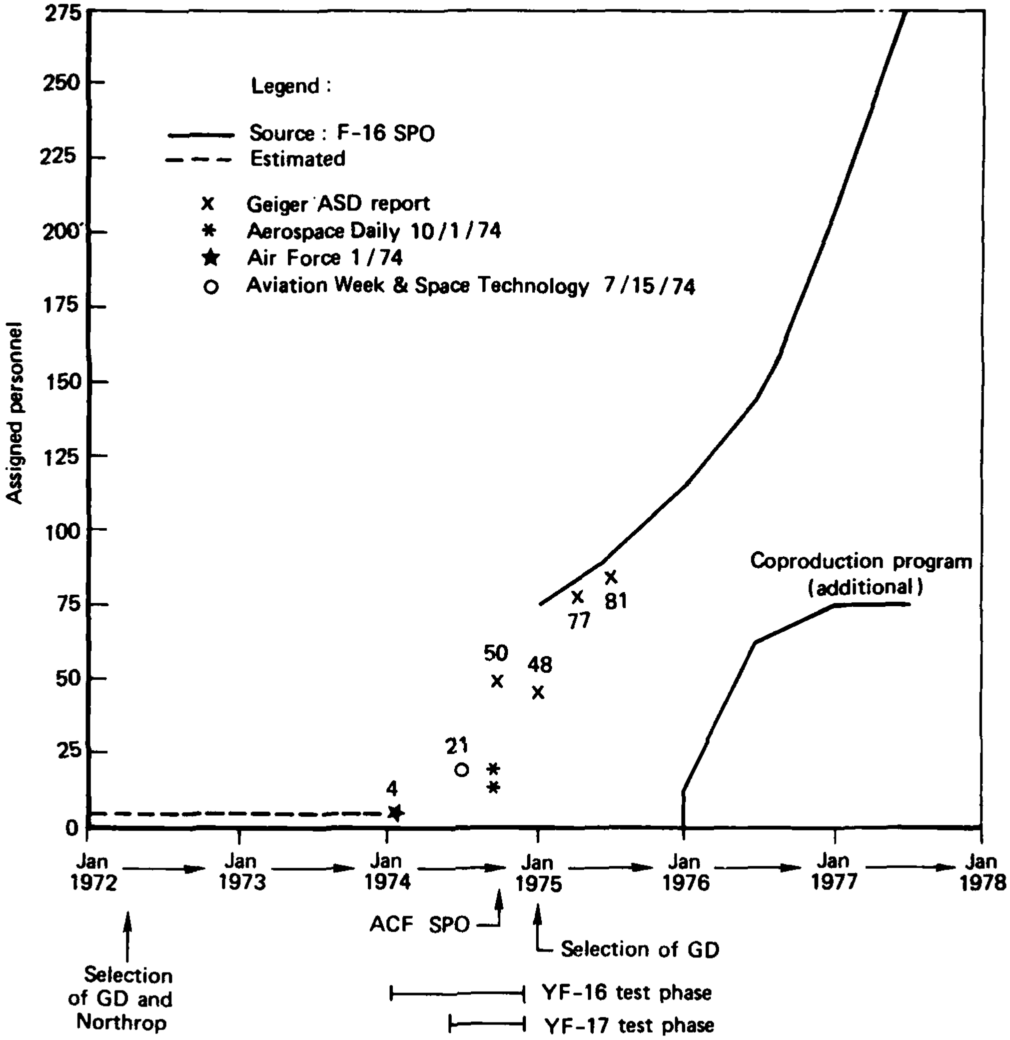


Fig. B.1—LWF/F-16A SPO manpower (AFSC only)

formal position of Deputy Program Manager for Logistics was established in the LWF Program Office, but the manning was still limited to one officer.

Test Program

Organization of the test effort was also one of the more innovative aspects of the program. As suggested by the Air Force Prototype Study Team, the Air Force and the contractors jointly tested the prototypes. The test program was designed and conducted by a Joint Test Force (JTF) consisting of three constituencies: the contractors, AFSC's flight test organization (Air Force Flight Test Center—AFFTC), and the Air Force's user-oriented test community (represented first by TAC and later by the Air Force Test and Evaluation Center (AFTEC) created in mid-1974). The entire test program was designed after the LWF prototype contract had been awarded but before flight test started. Although the plans were continually restructured throughout the test program, the initial exercise was valuable from a planning and familiarization standpoint. The missions were intentionally divided about evenly between envelope exploration and operational mission simulation.

Eight pilots participated: two from each contractor, three from AFFTC, and three from TAC/AFTEC. Only two men flew both designs: Col. James Ryder, the Commander of the JTF who represented AFFTC, and Col. Duke Johnson of TAC/AFTEC. The contractor's pilots flew only their own aircraft; the two service organizations each had two pilots (other than Ryder and Johnson), one assigned to the YF-16 and one assigned to the YF-17 (the TAC/AFTEC pilots were not graduates of the flight test school, although each had Master's Degrees in Aeronautical Engineering). This composition meant not only that service pilots entered the test program far sooner than in conventional programs, but also that the involvement of operations-oriented pilots began earlier.[15] Although pilots were chosen for each flight on the basis of suitability for that flight's objectives, a goal was to have the three JTF organizations participate equally. The decision not to assign "areas of responsibility" worked well in practice, even though the TAC/AFTEC pilots had no formal test qualifications. The contractors had support responsibilities, but TAC assigned three repair and maintenance people who were able to make several valuable contributions to the program.

It should also be recalled that the original test program emphasized gathering information about the two designs, without any need to select a "best" design. The source-selection objective was imposed after the test program was underway.

The test programs began at Edwards Air Force Base four months apart: the YF-16 in February 1974, the YF-17 in June 1974. Since the contractors had been given freedom to establish their own schedules and there was no intention of ever flying the two aircraft against each other, this stagger was not considered troublesome. However, when events required the test programs to reveal a winning design and source selection was scheduled for January 1975, the original plans for 12-month programs were scrapped and the remaining test points were carefully prioritized. The Air National Guard provided Northrop with a tanker to augment the YF-17s; refueling tripled the number of test points that could be accomplished in each flight. Northrop's ground-support team used a work schedule of three shifts, seven days per week during that time. Although the numbers of flights were not equal (about 320 for YF-16s and about 230 for YF-17s as of about 1 December 1974 when final test

[15]It should be noted that some of the flight-test design features, including early flights by Air Force pilots and rapid introduction of operationally oriented tests, were used to some extent in the A-X program.

data could be submitted), the amount of data accumulated on each aircraft was comparable.[16] The schedule compression is not considered to have either hampered the prototype program or biased the source selection.

The two contractors approached their test programs in different ways. General Dynamics relocated a large fraction of the YF-16 work force to the test site, including the project manager and the chief engineer. At the height of the program, there were about 350 General Dynamics employees at Edwards Air Force Base. This strategy improved communications and enabled General Dynamics to respond quickly and effectively to problems. Northrop, however, moved fewer people to the test site (under 100 at the peak of the program), apparently believing that their Hawthorne plant was sufficiently close. Because the project manager spent most of his time in Hawthorne, few decisions could be made on site. This reflects the general difference in the way General Dynamics and Northrop approached project management issues. General Dynamics created a separate project and had the project manager report directly to top-level corporate management. Northrop adopted no such special structure, retaining the matrix organization of its aircraft division.

The instrument data generated by the tests were provided in rough form to all members of the JTF (contractors were not given data from their counterpart's aircraft, of course). There was extensive subjective data collected as well. A "quick look" report from the debriefing held after each flight was prepared and pilots subsequently wrote detailed point-by-point reports. Although the SPO was in close, informal contact with the test program throughout, raw data was sent to it only on request.

TRANSITION TO A FULL SCALE DEVELOPMENT PROGRAM

In most of the areas that the LWF prototype phase was unconventional, the ensuing F-16 FSD effort was conventional: external pressures, contracting and management philosophies, test program, etc. It is significant that the "return to normalcy" began well before the prototype phase drew to a close.

Decision to Produce

When the decision to develop a missionized version of the LWF was made is not known with precision. As indicated earlier, the prototype program began in 1972 with no formal commitment or plans for any subsequent work, although the competing contractors believed there would be follow-on FSD and production work.[17]

Although there were some reports that a decision to produce one of the LWF designs was made as early as April 1974,[18] official statements at the time expressed no such commitment. For example, in a letter to congressional leaders, Secretary of Defense James Schlesinger indicated that full scale development and production of either the YF-16 or YF-17 was merely being seriously considered.[19] A month later, however, the Air Force submitted to the Office of the Secretary of Defense its Program Objective Memorandum, which proposed an augmented,

[16]Although the YF-16s were able to fly some missions that the YF-17s could not (because of time constraints), these were generally not very important to the source-selection question.

[17]For example, General Dynamics began doing production cost studies in late 1973 and working on the programming aspects of production in early 1974.

[18]See, e.g., *Washington Star-News*, 26 January 1975, p. A-7.

[19]See *Aerospace Daily*, 30 April 1974; *Air Force*, June 1974.

26-wing, full-strength active force structure to include the Air Combat Fighter—a missionized version of one of the Lightweight Fighters. It is reported that OSD decided to proceed with FSD of the Air Combat Fighter in June 1974, around the time the YF-17 made its maiden flight.[20] More specific details of the plans were revealed by the Air Force that summer: 400 ACFs would be produced; Northrop and General Dynamics would be issued Requests for Quotation[21] with responses due in November 1974; and the on-going test programs would be compressed to allow a January 1975 source-selection decision.

During the summer of 1974, the Air Force convened a study group to examine in detail how a missionized LWF could best augment the USAF tactical forces. Several different levels of avionics and weapon system sophistication (and consequent system mission capability and cost) were considered. Study team recommendations formed the basis for the mission specification included in the RFQ.

An important influence on these decisions was the potential for sales overseas. In the spring of 1974, Iran expressed interest in buying 250 missionized versions of the YF-17. Around the same time, a delegation from Belgium, The Netherlands, Denmark, and Norway was briefed on the production possibilities of the two LWF prototypes. In June 1974, these nations formed a consortium to find a replacement for their F-104s. Their interest in one of the LWF designs was conditioned on a U.S. source selection by January 1975, well in advance of the schedule then envisioned.[22] Although the decision to add the YF-16 or YF-17 to the USAF inventory was independent of the European interest in the aircraft, the acceleration of the program schedule was directly responsive to it. Less certain is the role that the consortium's interest played in the air-to-ground emphasis that was increasing during that time.

Transition Period

To enable them to prepare their FSD proposals, both General Dynamics and Northrop were awarded "transition" contracts of $4 million. They were to investigate certain specified design tradeoffs and submit an FSD proposal, a draft vehicle specification, and a draft system specification. That period was a somewhat hectic attempt to compensate for the informality of the prototype phase. The staffs of both the contractor and the SPO increased markedly as documentation demands mounted. Although the number of items designated for specification was low at first, it grew rapidly. The work began about six or seven months into the YF-16 flight test program and only about two or three months into the YF-17 test program. In other words, a significant amount of critical FSD-related work was initiated without the benefit of very much data from the flight-test programs.

The FSD proposals were judged by the following criteria (listed in general order of importance):

1. *Operational Capability.* Included here were assessments of the consistency with sys-

---

[20]U.S. Senate, Committee on Armed Services, Subcommittee on Tactical Air Power, *FY 1976/197T DoD Appropriation Authorization Act*, Hearings, 94th Cong., 1st Sess., Part 9, p. 4599. The formal OSD decision to proceed with the FSD phase of a major weapon system is theoretically made by the Defense Systems Acquisition Review Council at a milestone known as DSARC II. This did not occur until 11 March 1975.

[21]RFQs were in lieu of RFPs, which would have had to be sent to the entire industry.

[22]The French Air Force's indecision about procuring the competing Mirage lessened the chances that the French design would be selected. Also critical in the consortium's choice of U.S. design over its French and Swedish competitors was, of course, the opportunity to coproduce the system. Negotiations on that arrangement began late in the summer of 1974, with an MOU executed in June 1975.

tem specifications, the risk, and the potential for reducing continuing operating and support costs.

2. *Program Cost.* The cost proposals, which were to include development, production, flyaway, operational and support cost, were to be judged on their "reasonableness, realism, completeness, and the compatibility with design and cost objectives."
3. *Prototype/Weapon System Transition.* Examined here was the extent of the risk associated with any changes required in the prototype aircraft design to make it suitable for rate production.
4. *Adequacy of Program.* This referred to the soundness and adequacy of the proposals for development and integration efforts, taking account of both USAF and multinational aspects.

On 13 January 1975, the Air Force announced the selection of the YF-16. It awarded General Dynamics a $417.9 million contract for 15 FSD aircraft;[23] Pratt & Whitney received a $55.5 million contract for the F100 engines. Contract terms are presented in Table B.1. The General Dynamics contract was similar to most major weapon system FSD contracts in terms of documentation requirements, standard contract clauses, etc.

Table B.1

F-16 AND F100 CONTRACT PROVISIONS

Item	FSD	Production Options
F-16/General Dynamics		
Contract Type	FPIF	FPIF
Share ratio	90/10	70/30
Fee	11%	11%
Ceiling	130%	130%
F100/Pratt & Whitney		
Contract Type	FPIF	FPIF
Share ratio	70/30	70/30
Fee	10%	12%
Ceiling	120%	125%

SOURCE: USAF DSARC-II Briefing, 11 March 1975.

OVERVIEW OF PROGRAM MILESTONES

The F-16A single-source full scale development phase began three years after the Air Force solicited the aerospace industry for LWF proposals. Figure B.2 presents an overview of program milestones. Perhaps the most notable observation from this overview is that the

[23]The number of aircraft procured under the FSD contract was later reduced to eight (see discussion under "Cost Growth").

decisions to enter both full scale development and full scale production were made surprisingly early. The decision to commit one of the LWF designs to full scale development was made about six months before the completion of the prototype test programs (recall that the YF-16 and YF-17 test programs were roughly only 10 months and 6 months in length, respectively). The decision to produce the F-16A, represented by the DSARC IIIB go-ahead, was made about the time the last FSD test aircraft was delivered. As a result, delivery of production aircraft to the U.S. Air Force started somewhat before completion of the development test phase.

TECHNICAL OBJECTIVES OF THE PROTOTYPE PHASE

The RFP for the prototype program was a model of brevity. To provide a flavor of the prototype phase objectives, we reproduce a few excerpts from the RFP below. The description of program goals opened with these important phrases:

> The lightweight fighter prototype should demonstrate a capability for high performance in accomplishing maneuvers and tasks in a day visual fighter air combat environment. . . . [It] will be designed and fabricated to exhibit, in a prototype configuration, exceptional maneuvering and handling characteristics throughout its flight envelope while remaining light in weight (approximately 20,000 lbs at start of combat with full internal fuel) and low in cost. . . . The aircraft should provide maximum maneuvering capability at average combat weight . . . in this 0.8-1.6 Mach combat arena. Emphasis should be placed upon sustained turn capability at M 1.2 and M 0.9, 30,000 feet, level acceleration between 0.9-1.6 M at 30,000 feet and maximum fully controllable G at M 0.8, 40,000 ft.

A detailed mission was then specified, as follows:

- cruise 500 mi on external fuel
- drop tanks
- go to 30,000 ft altitude
- do four turns at max power, Mach 0.9
- accelerate to Mach 1.6 (max power)
- slow to Mach 1.2, do three turns at max power
- go to 20,000 ft
- climb to cruise altitude and speed
- cruise 500 mi home
- land, with 20 min loiter reserve

The emphasis was clearly on the demonstration of a basic flight vehicle, not a full weapon system. Another quotation from the work statement defines the desired scope of subsystems installation:

> Avionics subsystems installed should provide a minimum capability for communication and navigation during the test period. The design for weight and volume should include the volume and weight allowances made at suitable aircraft stations for avionics projected as being essential in an operational day lightweight fighter aircraft. . . . In the prototype the avionics cavities may be used for installation of test instrumentation.

For armament, only an internal gun, with appropriate sight head, and provision for IR missiles was specified.

A few phrases regarding the test and evaluation concept will serve to round out the overall intent of the RFP:

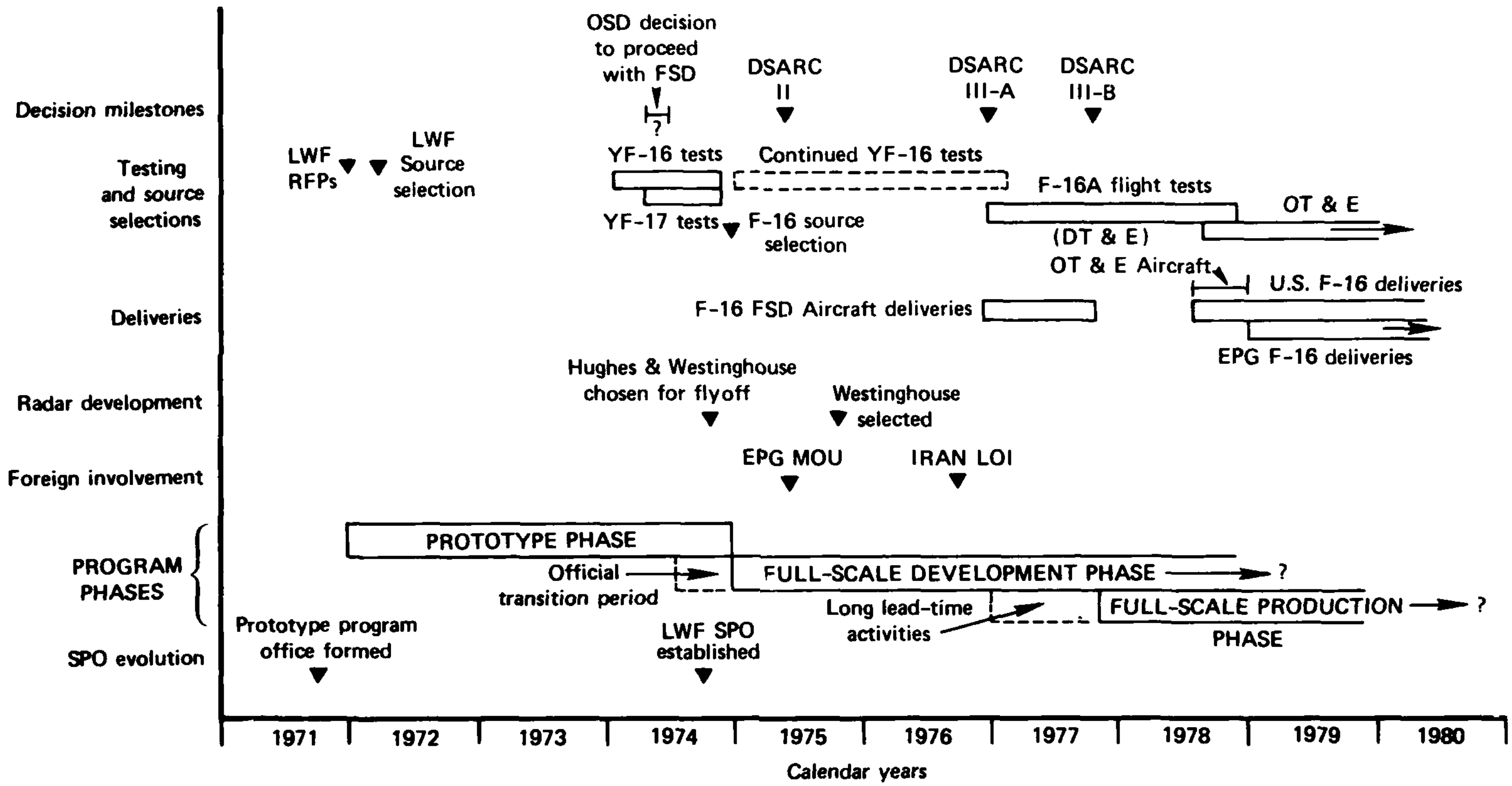


Fig. B.2—Overview of LWF/F-16 program milestones

> The test program will be limited to demonstrating the performance of the aircraft as a prototype vehicle rather than as a production model. It will include an evaluation of the advanced technology characteristics incorporated in the design to determine their utility, reliability and contribution to performance, stability, and control.

The RFP conveyed the intent of developing and demonstrating a portion of a weapon system (the basic flight vehicle, plus a modest amount of armament) but without most of the trappings of a full scale weapon system development program. Furthermore, the emphasis was clearly on evaluating the system's combat capability and utility, rather than simply assessing the technological innovations that might be involved. That intent was described in the section of the RFP where source-selection criteria are spelled out. Paragraph 2, titled "Specific Criteria—Technical Approach" contained the following:

> The specific criteria for judging superior designs and their order of importance to be used in evaluating the contractor's approach to meeting the performance/design goals are as follows:
>
> a. Achievement of the mission fuel, speed, structures and materials, avionics, armament/stores, propulsion system, and aircraft maneuvering stability and control goals.
>
> b. Maximum maneuverability with emphasis on maximum capability for the following in the given order of importance:
>
> (1) Sustained turn at M 1.2, 30,000 ft.
> (2) Sustained turn at M 0.9, 30,000 ft.
> (3) Level acceleration between M 0.9 – 1.6 at 30,000 ft.
> (4) Maximum fully controllable G at M 0.8, 40,000 ft.
>
> c. Small size, low weight/cost design approach.
>
> d. Excellent handling qualities and control response at and beyond maximum trimmed angle of attack throughout the air combat arena including an evaluation of spin resistance and positive spin recovery.
>
> e. Air-to-air gunnery tracking behavior at high G.
>
> f. Cockpit suitability for maneuvering tasks (including visibility).

No schedule was imposed for the development activity. In fact, the contractor was directed to propose his own schedule for the development phase so that he could make most efficient use of the resources, depending on his own design, facilities, and staff. The only time parameter specified was that the flight-test program would last for "a period of approximately 12 months," and that appears to have been intended only to help the contractor determine the cost of supporting the test program.

DESIGN SOLUTIONS

Five contractors submitted bids for the LWF prototype. Four of them (GD, Boeing, LTV, and Lockheed) were single-engine designs built around the F100 engine, while Northrop proposed a twin-engine design using the General Electric YJ101, which was still in development. (Northrop also submitted an alternative single-engine design using the F100 engine.) Only two contractors were chosen for prototype development work. Other than the number of engines, the two winning designs (Northrop YF-17 and GD YF-16) were remarkably similar in many respects. However, there were some differences, as shown in the weight and dimensional data summarized in Table B.2.

The two contractors started from substantially different reference points in developing

Table B.2

PROTOTYPE PHYSICAL DESCRIPTION

Item	YF-16	YF-17
Empty weight (lb)	13,200	17,390
Takeoff gross weight (lb)	21,400	24,760
Internal fuel weight (lb)	6600	6400
Wing area (sq ft)	283.5	350
Wing span (ft)	29	37.7
Fuselage length (ft)	46.5	55.5
Engine		
Number	1	2
Type	F100	J101
Max thrust per engine (lb)	24,000	15,000

their designs. Northrop had been working since approximately 1965 on a company-funded design, the P-530 Cobra. Throughout that time they had a staff of 40 to 50 people working in advanced design alone, together with other people in various support activities, and they accumulated about 5000 hours of wind tunnel time. Thus they had made a substantial investment and had a specific design configured in some detail, although without any actual shop drawings or other work necessary for fabrication of an airplane.

The Cobra was oriented almost exclusively toward the European market, where Northrop was trying to provide a successor to the F-104 and F-5 that had been sold to air forces around the world. The design specifications and configuration had evolved through several years of discussions and negotiations with the air forces of several European nations and had very little direct USAF influence (although Northrop had kept the USAF fully informed of their activities and had several times tried to get the USAF to help fund the initial development of the aircraft so as to make it more attractive to the Europeans). Northrop's own longstanding philosophy about what makes a successful fighter aircraft (small, simple, low-cost aircraft capable of outstanding maneuverability in the subsonic and transonic speed range) was largely consistent with that of the people who dominated the LWF requirements formulation, so the general P-530 design was substantially responsive to the LWF RFP.

Work on LWF designs at GD began around 1964. It drew on experience in Southeast Asia that suggested the value of an internal gun, and on the lessons learned from the difficulties encountered in making radar-guided missiles effective. When the F-X concept formulation studies were done in 1966, GD responded with two parallel efforts. One was fully responsive to the F-X design and performance requirements, and the other was a smaller, more austere "gun fighter." Although GD lost its bid to participate in the funded F-X/F-15 concept formulation phase, it maintained a continuous study on LWF alternatives. The technical work emphasized a blended lifting body combined with maneuver flaps. Throughout 1968/1970, a staff of 10 to 15 people was maintained and a considerable amount of wind tunnel work was done on over 70 different configurations. But although it is clear that GD had been working on advanced fighter aircraft concepts for several years, it is equally clear that before the LWF

RFP they had not decided on a specific design to the degree that Northrop had in their P-530. Not until early in 1971 did GD focus on a single design approach, embodied in the "400 series" from which grew the "401" (the YF-16 proposal). By the time GD replied to the prototype LWF RFP, they had accumulated about 1400 hours of wind tunnel test on the 400-series designs.

Northrop apparently had a more completely defined design concept around which they could build a proposal but was more constrained in utilizing new technology for the LWF without making major changes in their design. Conversely, GD was fairly unconstrained in selection of design elements but was less far along in the formulation of a specific, integrated design when the RFP appeared. For example, in an *Aviation Week* article (January 7, 1974), Lyman Josephs (F-16 Program Manager at GD) is quoted as saying the decision to use the relaxed static stability in the YF-16 design was made only two weeks before the prototype proposal was submitted. This difference in starting points is reflected in the two designs; the GD YF-16 was somewhat more adventurous and radical in technological content, while the Northrop YF-17 was somewhat more conventional. The specific differences in key design features will be described below.

Both contractors had a chance to fine tune their design ideas during a study of advanced fighter concepts funded by the Air Force and conducted in 1970 and 1971. That study was mostly a parametric investigation of the performance potential for a few alternative configurations, but it did give both the Air Force and the contractors an opportunity to sharpen their ideas about a preferred performance specification for a lightweight fighter.

Both of the winning contractors had already accumulated a substantial body of information on the LWF concept before receipt of the RFP. That preparation, done in close cooperation with the Air Force, is probably one important reason for the successful prototype phase. Major design approaches had been selected, and a high degree of mutual understanding existed regarding the key objectives of the program.

The resulting designs shared certain features: little or no emphasis on survivability/vulnerability aspects, short (one year) structure lifetime, no emphasis on producibility or life cycle cost (two items to be hand built on soft tooling), and minimal investments in operational safety features (back-up power supplies, elaborate ejection seat, etc.). However, the YF-16 and YF-17 designs differed in several important respects. The most obvious difference was in propulsion systems. The YF-16 used a single F100, an engine already developed for the F-15 program. By the time of YF-16 first flight in early 1974, the F100 engine had already completed MQT and had accumulated over 2000 engine flight hours in the F-15 test program. Thus the engine was considered a low risk element in the YF-16 program. Conversely, the YF-17 was designed around twin J101 engines, a model developed by General Electric largely as a private venture. When the YF-17 design contract was awarded early in 1972, the J101 engine had not even been run on a test stand in its final configuration, and it would be another seven years before MQT. Thus, the YF-17 propulsion system represented a substantial risk area. Ironically, during the prototype flight-test program the F100 engine caused more aircraft down time than did the J101.

A second important difference was the cockpit design. The YF-17 had a conventional two-piece canopy (forward part fixed) and a rather conventional seat that was tilted back 18° (rather than about 15° in the F-15 and the F-4). The YF-16 used a one-piece "bubble" canopy and a seat that was tilted back 30°. These differences served to make the YF-16 pilot better able to sustain high "g" forces and to give him better visibility than the YF-17 pilot. Both aircraft featured raised heel lines for the pilot which, in combination with the tilted seat back, added considerably to pilot comfort and "g" tolerance.

The inclined seat did not represent a major technical problem (but it was still an innovation, simply because of the break with traditional practice and because of the benefits it provided). However, the one-piece bubble canopy had numerous technical problems. Undistorted vision required use of a special polycarbonate material. It was quite soft and subject to scratches, so a protective film had to be added that required highly sophisticated processing. Furthermore, canopy strength (ability to sustain bird strikes) was a matter of serious concern, and the thickness was increased after initial tests.

Probably the most important difference between the two designs was in the flight-control system. The YF-17 control system was conventional, with standard stick and rudder controls in the cockpit, and conventional mechanical linkages to the tail surfaces (pitch and yaw control). The ailerons were controlled by an electronic "fly-by-wire" system (no mechanical link between the pilot's control stick and the aileron surfaces). The autostabilization system common to all high performance aircraft was used, but a design goal was for the airplane to be stable and spin resistant even without the autostabilizer. The good handling performance of the airplane, especially in the subsonic regime, is probably due more to the refinements in aerodynamic configuration than to any special sophistication in the control system.

The control system on the YF-16 was decidedly unconventional. First, it was entirely fly by wire, with no mechanical linkages to any control surface. A quadruple-redundant analog computer controlled all aerodynamic surfaces by means of electrically powered servo motors.[24] Although the idea of fly by wire had been around a long time and had seen limited service (YF-12/SR-71), always before there had been a back-up mechanical linkage. The second special feature of the YF-16 was a "relaxed static stability." A conventional airplane is designed with the center of gravity ahead of the aerodynamic center of pressure, so that aerodynamic and inertial forces tend to make the airplane go in the direction the nose is pointed. This is fine most of the time, but when a maneuver is demanded in the pitch plane, some of the control power is used to overcome the built-in stability. This problem is especially troublesome in supersonic aircraft because the aerodynamic center of pressure tends to move aft as the speed increases from subsonic to supersonic. Thus, an airplane designed to be stable at subsonic speeds is even more stable (and hence less maneuverable) at supersonic speeds. In the YF-16, the airplane was deliberately built to be slightly unstable at subsonic speeds and just barely stable at supersonic speeds, and the flight control system was given the job of making the airplane behave properly. This idea had been discussed for a long time, but the YF-16 was the first time anyone had been bold enough to build and fly such an airplane for other than purely research purposes.[25]

Another novel aspect of the YF-16 flight-control system was the side-mounted "force stick." In most airplanes, the pitch and roll control is through a stick mounted on the floor of the cockpit and extending up between the pilot's legs. In the YF-16, the "stick" is simply a handle mounted on the right-hand cockpit console, and the pilot inputs signals by applying force to the stick. The stick itself is a stiff cantilever beam with a maximum displacement at the top of about one quarter inch from neutral in either direction. A control stick of this type had been flight tested in an experimental aircraft, but the YF-16 was the first application in a service-configured design. A small, rigid stick has certain advantages in that it cleans up the cockpit (a lot of space is needed for movement of a conventional stick, and space is at a

[24]A special emergency power generator was also installed, to ensure flight control if the engine failed.

[25]A substantial amount of research and flight demonstration had been completed before initiation of the LWF prototype project. Perhaps the most critical step in making a relaxed-stability configuration practical was the evolution of fly-by-wire technology to a point where reliability met operationally satisfactory levels.

premium in a small fighter cockpit) and saves some weight. Other advantages are reduction of friction and "dead zones" typical of a conventional moving control stick and elimination of need for pilot arm movement which is difficult during high "g" maneuvers. One disadvantage is that the pilot is denied any physical cue about how much of his available control power he is using at any instant. The YF-16 flight tests indicated the desirability of introducing slightly more movement in the stick so as to give the pilot better physical cues. However, most pilots quickly adapt to the side force control stick and like it.

Some additional aspects of the fly-by-wire system need to be mentioned here. Since the entire control of the airplane is handled by means of an analog computer, the handling characteristics can be modified by adjustments to the computer. That tends to be much easier and quicker than modifying the complicated mixers and feel controls used in a mechanical control system. This feature turned out to be quite important during the flight-test program, and will be discussed below. Finally, this kind of control system makes it possible to program the computer so that the pilot cannot exceed the normal flight boundaries of the aircraft. That is, he cannot pull the wings off, or enter a high-speed stall. With this arrangement the pilot can engage in air combat maneuvers "with reckless abandon." He can devote all of his attention to the tactics of the situation, without having to worry about the process of flying his airplane right to the limit of its performance without exceeding that limit. This should be of substantial value in combat, especially to less than expert pilots.

Finally, two other differences between the designs deserve mention. One was that the YF-17 made greater use of composite materials in the structure. That had been a rather prominent "technology demonstration" goal in the program, but it turned out to be one of the less important advances in terms of final value to the weapon system capability. In fact, lessons learned during the prototype tests led to a reduction in the use of composite materials in the full scale F-16A program (see discussion of test program for details). The other difference was the all-digital avionics system in the YF-16 (except for the flight-control system, which remained analog).

TEST PROGRAM DESIGN

The objective of the flight-test phase was to evaluate the potential operational usefulness of the design, especially the new technology features incorporated in the two different configurations. Furthermore, the tests were to be conducted within one year (although the total test program was scheduled to run for 16 months, because the YF-17 first flight started about four months later than that of the YF-16). This posed an exceptional challenge, because normally the technical testing of such new and novel designs would have extended over at least a year, before any operationally oriented testing would be started. The one-year limit was dictated by the austere funding level of the overall program: The contractors were expected to fully support the aircraft during test, and those costs had to come out of the single allocation awarded to each contractor.

Although short and austere, the test program was apparently adequate. No evidence was found to indicate that more testing of the prototypes would have yielded a different source selection or would have materially aided the transition to FSD.

A substantial effort was devoted to planning the flight-test program, starting early in the prototype development phase. To facilitate an early emphasis on operational suitability testing, Col. Thurman (who became director of the Prototype Program Office in June 1973) directed that the flight-test planning and the actual testing itself should be conducted by a

troika consisting of personnel from the contractor, the Air Force Flight Test Center, and the Tactical Air Command. In October 1973 the Program Office issued a memorandum defining the priority of objectives in the test program:

1. Flight envelope
2. Energy maneuverability
3. High angle-of-attack flight characteristics
4. Tracking performance
5. Weapons/engine/airframe compatibility
6. Mission performance
7. ACM suitability

Three months later, a briefing prepared by the SPO suggested the following distribution for effort among slightly different categories:

	Percent
Airworthiness	15
Armament/engine/airframe/evaluation	20
Stability and performance	30
Operational utility	35

The rate at which testing flight hours were accumulated is shown in Fig. B.3.

Not only were operational objectives emphasized much earlier than normal in the test program, but the actual flying tasks were distributed about evenly among contractor, AFFTC, and TAC pilots. That is, each got to do about one-third of the flying, and each pilot had an opportunity to participate in most of the different test phases. The last feature had some exceptions—the contractor pilots did the most hazardous flight safety demonstrations such as first flight and high-speed flutter tests, and the TAC pilots had a disproportionate share of the air combat maneuvering flights. Other novel aspects evolved from the basic policy of three-way participation. An Air Force pilot (from AFFTC) flew the YF-16 on its third flight, and a TAC pilot flew the 12th flight. It was highly unusual for Air Force pilots to fly so early in the test program, especially considering that the TAC pilots were not accredited test pilots (although they certainly were highly qualified and skilled pilots). The ready acceptance of the novel features in the F-16 by TAC when FSD was being contemplated is attributed in part to the heavy involvement of operational personnel and the prominence of operational test objectives throughout the test program. It has been claimed by some that such early involvement by operational personnel will lead to a more "mature" system straight out of FSD. (Normally, heavy user participation in a flight-test program does not start until the initial production aircraft are delivered to the using command, and by then it is too late to change very much in the design without suffering substantial expense and delay.)

The degree of success achieved by this testing approach depends somewhat on the observer. Air Force personnel at all levels seemed universally enthusiastic about it and consider the LWF test program a success. The two contractors are less enthusiastic because early Air Force involvement and early emphasis on operational testing diluted their opportunity to obtain technical information about their designs. In any case, an evaluation of the novel test procedure has to be tempered by the fact that the entire prototype test program was exceptionally trouble free and that the experience cannot be logically explained by the form of the

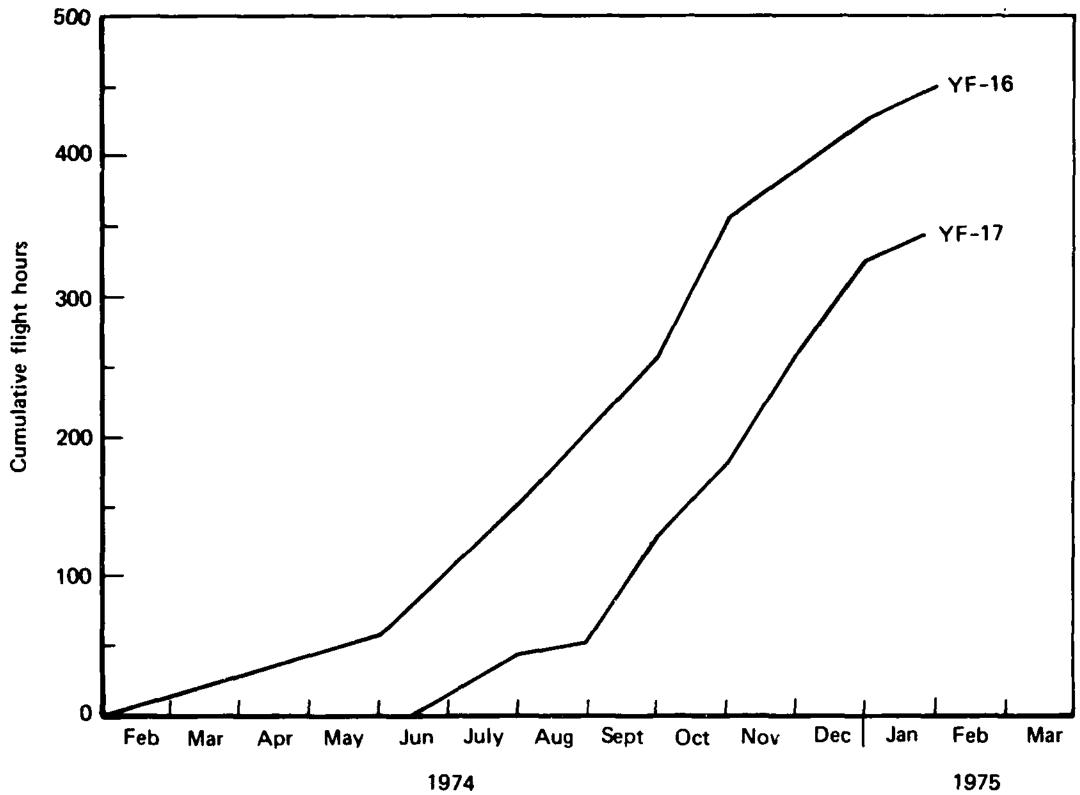


Fig. B.3—LWF flight test schedule

test program alone. In fact, if either of the designs had run into serious technical problems that demanded extensive modifications and retest, then the overall effectiveness of this test approach would probably have looked much less attractive. The contractors both point out that the Air Force should be careful about using the LWF program as a model on which to base future test programs, because history suggests that rarely will a test program run so smoothly.

TEST RESULTS

The product of the test program has to be evaluated in terms of how, and what, it contributed to the source selection and the subsequent full scale development of the F-16.[26] The

---

[26]The extent to which these criteria are compatible with the original objectives of the LWF program is open to some debate, because of the apparent ambiguity of original program objectives. However, the Air Force and contractor project personnel appear to have acted from the beginning as if they were preparing for source selection and full scale development.

discussion of contributions to FSD will necessarily emphasize the YF-16 flight-test results, but some pertinent information on YF-17 test results will also be recounted. Since the details of the test program and results are fully documented in technical reports, we note only a few aspects here.

When we examine the evolution of the YF-16 into the F-16A/B weapon system, the configuration changes can be conveniently grouped under six headings:

- Increased avionics capability
- Increased external store capabilities
- Other operational improvements
- Producibility, cost, weight, and function changes
- Prototype-unique changes (removal of test instrumentation)
- Prototype evaluation changes

The first four of those changes are important to the extent that they represent areas of technical development that were not tested and demonstrated during the prototype phase. The YF-16 was basically a flight vehicle demonstrator, and only a few aspects of a full weapon system were included. For example, the YF-16 had no radar,[27] no fire control system, and only a rudimentary stores management system. It did have a gun and a HUD (Head-up Display), although the HUD would undergo some modifications when it was integrated into the overall fire control system on the F-16A. Thus, the prototypes yielded little direct information on the quality or performance of the weapon system avionics. The remainder of this appendix mainly concerns changes stemming from evaluation of the prototype.

The prototype flight tests yielded major contributions in several areas: validation of flight performance, stability and control, flutter, human factors, and a few key subsystems. Each of these will be discussed in turn below.

Flight Performance

Tests were conducted to validate the predicted speed-altitude envelope, cruise efficiency, and EM characteristics. To conserve time, much of this testing was conducted piecemeal as a part of other test goals. Neither model exhibited substantial deviations from predicted performance levels. After source selection, a decision was made to strictly minimize any changes in external configuration of the YF-16 so that the FSD airplane would be assured of similar performance.[28] The prototype flight tests were extensively compared with predictions based on wind tunnel and analysis results, and those predictions were validated to a high degree. Therefore, when it was proposed that the fuselage be lengthened and the wing area increased, the effect of those modest changes could be analytically predicted with high confidence. This fact not only added confidence to the DSARC II decisions, but also resulted in a smaller fleet of FSD test aircraft because the aerodynamic test program of the F-16 A/B could be somewhat truncated.

Subsequent flight tests of the FSD configuration substantially validated the engineering predictions. There were, however, some surprises. The most important was an unanticipated stall problem encountered at high pitch angles.

[27]Prototype #2 did have a ranging radar installed to support the gun aiming system, but that was considered a piece of test equipment and not a part of the prototype being tested.

[28]The decision against additional changes in external configuration was not without dissent. Maintenance people, and those concerned with physical vulnerability, wanted to make additional changes in external lines to enhance their own particular disciplines, but they were overruled.

Stability and Control

One of the major design objectives of the LWF program was to achieve excellent handling qualities, especially at elevated g loadings and high angles of attack. These goals were substantially demonstrated during flight test. The YF-16 exhibited low buffet intensities, adequate roll rates, and good damping about all axes. The only significant problem was a tendency for inertial roll/pitch coupling under certain extreme combinations of angle of attack and dynamic pressure, and that had been predicted before flight test. A recommendation was made that the electronic flight control system should be modified to minimize the probability of such a problem.

Flutter

The YF-16 tests qualified the configuration for flutter characteristics, both clean and with some external loads. One problem noted was first thought to be wing tip flutter but turned out to be a coupling between inertial forces and the roll axis of the flight control system. Modifications to the control system solved the problem. This information was of substantial value because it gave confidence to the engineers designing the subsequent F-16A structure and may have permitted some slight reduction in FSD flight-test duration. However, the F-16 A/B had to be qualified for many configurations not tested during the prototype phase.

Human Factors

The general arrangement of the cockpit and the novel reclining seat of the YF-16 were thoroughly tested and validated. A few changes were suggested by the test pilots and incorporated in the FSD design. Since this is an area that has frequently led to extensive changes during FSD, the prototype test results probably yielded considerable savings in FSD cost.

Subsystem Validation

The novel control system used in the YF-16 (fly-by-wire, side force control stick) posed lots of potential for trouble, and in fact many problems did arise. However, they were all quickly corrected. Many examples of "fine tuning" of the control system occurred during the flight test program.[29] The result was that when FSD started the contractor had extensively tested, refined, and validated a novel control system that contributed substantially to the flight performance of the airplane. Again, the FSD test program was probably somewhat reduced because of that fact.

The engine was another major YF-16 subsystem that was extensively tested during the prototype phase. Although not a completely new item, the engine did cause some problems, and significant modifications were made to the fuel control system.

[29] One example of the design flexibility inherent in this approach is the automatic compensation for yawing moment caused by firing the gun (which is mounted to one side of the aircraft center line). Such yaw compensation was included in the original computer, but flight tests revealed some limitations in its performance. Fixes to such problems were easily incorporated during FSD.

The one-piece canopy for the YF-16 was also extensively tested. Bird impact tests led to a redesign involving thicker material, but the one-piece design concept was enthusiastically endorsed by the pilots.

Secondary Contributions

One limitation of the YF-16 prototype was that the structure was to be completely redesigned for the full scale development article. During development of the YF-16 it was decided that no attempt would be made to "save" any of the shop drawings or tooling from the prototype phase. That seemed consistent with the formally announced overall guidance given to the contractors that they should not count on any subsequent development or production of their designs. It was also a major cost saving measure, permitting more of the prototype phase resources to be devoted to the primary goal of demonstrating advanced design concepts.[30] Another factor complicating any use of YF-16 structure test data is that the YF-16 structure was deliberately overdesigned by a stress margin of about 25 percent. That was done so that certain high-stress flight maneuvers could be performed without having first to complete an extensive static proof test of the basic structure. During the prototype flight tests the structure did not cause any problems at all, even though it was designed without any significant fatigue criteria (an airframe lifetime of only a few hundred hours was envisioned).

When the FSD phase was started, the basic structure design concept was retained but the detail design was completely redone, and this time to much narrower margins. The contractor stated that not a single part was interchangeable between the prototype and the FSD airplane. Some redesign was also required because of the 10 in. increase in fuselage length and the addition of 20 sq ft to the wing area of the F-16A relative to the YF-16.[31] A comparison of YF-16 and F-16A weight breakdown, shown in Table B.3, suggests the degree of change between the two versions.[32]

Because the YF-16 structure had been designed with intentionally conservative margins, and the F-16A had been completely redesigned to more conventional margins, only limited observations can be made regarding the possible benefits obtained from the prototype tests. One test product relating to structure was in terms of composite materials use. The general experience of both designs led to only a modest use of composites on the F-16A. The YF-17 had made extensive use of composites on doors and access panels, with unsatisfactory results. Fasteners pulled through, edges frayed and caught on the clothing of maintenance people, and the weight savings were small. That idea was discarded. The YF-16 had employed graphite composite skins on the tail surfaces, and on the first (albeit inadvertent) flight, the horizontal tail tip was dinged against the runway. The composite skin proved more difficult to repair than a metal skin would have been, but the design was retained because of its superior stiffness and low weight in that particular application.

---

[30]Northrop took a somewhat different approach, and the YF-17 structure was more nearly a pre-production design. Some of the apparent cost differences between the two prototype development programs may be attributed to this feature. However, since the Air Force did not elect to complete that design, the differences between the YF-17 and the YF-16 in that regard cannot be substantiated.

[31]The fuselage was lengthened so that a single basic structure could be used for both the single- and two-place versions. The wing area was added to maintain wing loading while overall weight was increased.

[32]Aircraft weight, especially for "equipment" items, changes continually during the system lifetime. Thus the weights shown in Table B.3 for the F-16A provide an impression of the degree of change from the prototype to the FSD design but should not be interpreted as representing exactly the operational F-16A configuration.

Table B.3

WEIGHT COMPARISON, YF-16 TO F-16A

	YF-16 Prototype No. 2	F-16A#6
Item	Actual	Actual
Structures group	6507	7180
Propulsion group	3395	3671
Fixed equipment group	3415	3860
Weight empty	13295	14738
Useful load (crew, etc.)	1418	961
Payload (munitions)	605	619
Zero-fuel weight	15318	16318
Full internal fuel	6511	6775
Combat weight	21829	23093
External tanks	0	880
External fuel	0	4810
Takeoff gross weight	21829	28783

Another interesting example of how a prototype can be used was the testing of fasteners. GD designed the two YF-16 vehicles with different types of fasteners so as to gain experience on which were most suitable. Such a full scale experiment could hardly be conducted during a conventional full scale development program.

The prototype also provided only limited information regarding reliability and maintainability. Since major changes, or complete substitutions of different items, occurred in most of the subsystems, the data collected on YF-16 subsystem reliability was of little value during FSD. This seems an inevitable product of an austere prototype phase because in many cases equipment, components, and subsystems were "borrowed" from existing or obsolete aircraft. That simplified the design process, reduced development time and cost, and assured that the test program would not be unduly hampered by reliabilty of those elements because most of those used were fully qualified and mature. However, when a large production program was contemplated it became desirable to evaluate the selection of such components with a different set of criteria, causing many of them to be changed in the full scale development design. Some information was gained from the prototype in terms of the local environment (vibration, temperature, etc.) imposed on some of the subsystems, and that helped in specification

of the equipment during FSD. Furthermore, the prototype aircraft were used extensively during the early portion of FSD to flight qualify the new components and subsystems, thereby accelerating the flight-test program and probably saving the cost of building at least one more FSD test article. This potential benefit of prototyping can be effectively exploited only if the prototype was designed to closely simulate a fully operational aircraft, and if no major design changes occur from prototype to full scale development configuration.[33]

A modest amount was learned about the maintainability of the YF-16, even though that was not a program objective. TAC provided three senior master sergeants to assist in maintaining the aircraft; they provided many ideas for improving access and location of internal components, and those ideas were incorporated during FSD. In general, they validated the good design features and recommended changes in the poor features. Nearly 200 "system evaluation reports" were prepared on the YF-16.

Engine/airframe compatibility had been a source of major trouble in some previous aircraft. The F-111 is perhaps the most notorious example, but others since then have not been free of problems in this area. The YF-16 benefited because it used an existing engine that was already in production and had some flying experience in the F-15. Even so, it was not trouble-free during the prototype test phase. A special fuel control override was installed on the engine to assure power availability after one YF-16 was almost lost when the engine stuck in idle power during flight. The YF-16 tests contributed to fuel control improvements that were also fed back into the F-15 program. The overall integration of the engine and airframe was demonstrated, and only a few detail design changes were made from prototype to FSD. One such change was a simplification; prototype tests revealed that inlet blow-in doors were not needed. Thus the inlet on the F-16A does not have a single moving part.

Source Selection

The contribution of prototype phase flight-test results to source selection is difficult to quantify because source-selection proceedings are not available. However, there is a substantial store of unauthorized and unverifiable anecdotes to draw from. One assertion, which seems quite plausible, is that if a paper competition for FSD had been held between the two designs, without benefit of flight demonstration, the YF-17 would have probably won simply because few people would have cared to accept the technical risks inherent in the YF-16. It was also asserted that the YF-16 actually out-performed the YF-17 in a number of important areas during the prototoype flight-test program, and the Air Force personnel connected with the flight test seemed convinced that the correct choice had been made. Assuming the validity of those two assertions, then the prototype program resulted in a different, and better, airplane than would have been selected on the basis of a conventional paper competition.

Even that tentative conclusion has to be qualified because changes from the prototype configuration would have been made regardless of which design was selected, and it is conceivable that an "F-17A" could have emerged from FSD that was equal, or even superior, to the F-16A. Both aircraft did undergo some subsequent transformation, but the YF-17 evolved into the Navy F-18 under a different set of objectives. It is therefore impossible to make any quantitative argument about which design was best; the prototype performance comparison

[33]In this context, a "major" redesign (sufficient to nullify prototype use in defining subsystem environment or in testing and qualifying components) would be any design change that caused either a shift in component location or a change in the temperature, vibration, or other environmental characteristic of the volume wherein a subsystem was mounted.

data are not available, and subsequent development of the two designs was toward different objectives. We must therefore rely on the cumulative judgment of the Air Force participants in the development program and the final source selection. Their choice of the YF-16 appears unanimous and unreserved, and that is the sole basis for our conclusion that in this case the prototype phase led to selection of a design that was different from, and superior to, what the conventional source-selection approach would have yielded.

Transition Phase

The mission capability and flight vehicle performance goals for the operational configuration were spelled out in somewhat more detail than for the prototypes. A few excerpts from the Proposal Instructions follow:

> System performance contained in these instructions should be viewed as the best estimate of currently perceived design capability. While the contractor must address both the required and desired performance and specifications contained herein, the Government's intent is to provide considerable flexibility to each contractor to propose a program which takes maximum advantage of prototype experiences to produce the lowest LCC aircraft with acceptable performance on realistic . . . schedules. . . .
>
> The Air Combat Fighter will be designed to exhibit superior performance and handling qualities for the tasks associated with fighter air combat. The system must perform the tactical air missions of fighter sweep, escort, combat air patrol and intercept under clear air mass and limited adverse weather conditions. As a secondary role, the ACF must perform the air-to-ground tactical missions of close air support and interdiction under visual weapon delivery conditions. In addition, Group A provisions will be included for the delivery of tactical nuclear weapons during limited adverse weather conditions. The ACF is thus a multi-purpose fighter designed primarily for air superiority with a complementary but extensive air-to-ground capability. . . . The ACF operational configuration will be a direct derivative of the prototype designs with principal changes resulting in improved produceability, reliability, maintainability and operational utility.
>
> The system performance described in [Table B.4] is based on the ACF Air Superiority Design Mission, the ACF Air-to-Ground Mission and the Ferry Mission. . . . The desired numbers represent a level of capability sought by the Air Force but only if they can be met without compromising the cost goal. . . .
>
> Operational avionic equipments include a coherent pulse doppler search/track radar, heads-up display, stores management system, radar and TV heads-down display, passive radar homing and warning, active ECM pod provisions, inertial navigation system, TACAN/VOR/ILS, two UHF transceivers, air-to-ground IFF/SIF, secure voice, UHF/ADF, gun camera, and Group A (space, cooling, wiring, and power) provisions for: laser spot tracker, data link, radar ground mapping, carriage delivery of nuclear weapons and radar-guided missiles. The installed avionics package described within the ACF System Specification will not exceed $750,000 (FY 75 dollars, 1000 aircraft). Contractors are encouraged to conduct tradeoffs among the avionics components to remain within this cost ($250,000, FY 75 dollars, an average of 1000 units must be allocated to radar).
>
> Air-to-air armament includes the carriage of four AIM-9J/L missiles, an M-61 20mm cannon with 500 round capacity, and Group A provisions for carriage of two radar missiles (replace two AIM-9J/L).
>
> Air-to-ground armament includes an M-61 20mm cannon with 500 round capacity and accommodations for MERs, dispensers, launchers to carry the following ordnance types as a minimum:
>
> (a) General-purpose bombs
> (b) Electro-optical and laser-guided bombs/missiles
> (c) Dispenser munitions

Table B.4

ACF SYSTEM PERFORMANCE

Item	Required	Desired
Radius (ACF design mission) (n mi)	500	600
Sustained turn rates		
1.2 M/30K (deg/sec)	6.3	>6.8
0.9 M/30K (deg/sec)	8.8	>9.0
Level acceleration time		
0.9 - 1.6M/30K (sec)	80	70
Max g 0.8M/40K	4.0	>4.5
Ferry range (n mi)	2200	2600
Radius (ACF A/G mission)		
(2) MK-84/ALQ 119-3 (n mi)		>400

The proposal Instructions also make clear a shift of emphasis in the weapon system, away from a "pure" air-to-air day fighter and toward a multi-purpose system with some limited capability for air-to-ground and adverse weather operations. This shift contributed to the changes in vehicle configuration, as indicated in Tables B.3 and B.5. The available information does not permit an accurate accounting of the individual effects of the different kinds of changes, and we can only observe the overall effects by comparing the prototype with the final F-16A. A summary comparison of physical characteristics is shown in Table B.6 to augment the performance data shown above. For comparison, similar data are also shown for the YF-17.

F-16 PROGRAM COSTS

Previous sections of this appendix examined the institutional and technical aspects of the LWF/F-16A program. This section addresses the cost implications: What additional costs were incurred because of the prototyping effort? Were there economies in subsequent acquisition phases that would offset, to at least some degree, the apparent out-of-pocket costs of prototyping? Were there other benefits from a cost standpoint, such as the ability to make better predictions of total program costs before the commitment of a large investment in the program?

The F-16 program costs and cost history were analyzed to (1) determine the cost of the prototype phase and its fraction of the expected total program costs; (2) draw comparisons with other aircraft acquisition programs, especially those characterized as conventional (or

Table B.5

F-16 CHANGES FROM THE PROTOTYPE

Emergency power unit modified and relocated
Ejection seat
F100(3) production engine
Improved removal provisions
Jet fuel starter
Resized horizontal tail
Additional graphite composites
Added tail hook
Expanded external stores capability
Wing area expanded 20 sq ft
10 in. fuselage extension
Increased landing gear capability
Deleted blow-in doors
Improved access provisions
Multi-mode radar
Missionized avionics

SOURCE: DSARC III Briefing, 11 March 1975. Other changes have been incorporated since 1975.

Table B.6

ACF CONFIGURATION

Item	YF-16	F-16A	YF-17
Takeoff gross weight (int. fuel only)	21,829	23,093	24,760
Useful load weights (lb)			
Fuel	6511	6775	6400
Ammunition	281	281	281
Missiles	324	338	342
Fuel weight/aircraft weight	.298	.293	.258
Wing loading (lb/sq ft)	78	77	71

concurrent) acquisition programs without a competitive prototype phase; and (3) evaluate whether, in fact, the existence of a prototype phase in the F-16 program improved the cost estimates of the subsequent full scale development and production phases.

The F-16 program is unique in several respects, which precludes a straightforward cost analysis. For example, development cost benefits were derived from the previous development of the F100 engine as part of the earlier F-15 program, and the cost of most of the subsequent development of the engine was shared between the F-16 and F-15 programs. The second unusual feature of the F-16 acquisition program is the large multinational buy. The

F-16 production includes the USAF buy of 1388 procurement aircraft, plus 348 that were on contract for the European Participating Group.[34] Moreover, the F-16 foreign military sales master plan predicts large sales to other countries. This foreign procurement started at an early point in the program, which means that the cost of the higher priced early production aircraft, normally paid for by USAF, was shared by the foreign buyers.

Program costs presented herein cover only the USAF portion of the acquisition. Because of the above-described abnormalities of the F-16 acquisition program, the tracking of cost growth will be difficult. Nevertheless, we can make approximations and obtain insights into the value and shortcomings of the prototype concept by examining the evolution of the LWF competition and the F-16 program.

In January of 1972 the Air Force issued an RFP stating that a total of $90 million was being made available for a LWF prototype program. This is equal to about $176 million in FY 81 dollars. This sum was to be used for the design, development, and fabrication of the prototype aircraft; it would include government-furnished equipment and a year of joint test and evaluation of the aircraft. The form of the prototype contract—cost reimbursable but with a maximum ceiling cost to the government—gave the SPO access to the contractor's internal cost and financial records but did not commit the government to cover cost overruns. Although it was understood that the contractors could simply deliver their best effort, whatever it was, within the sums provided, the magnitude of the potential acquisition program for the aircraft (despite public statements that the only purpose of the development was to evaluate new technology) insured a maximum effort from both competitors and the use of corporate funds to the extent deemed necessary to meet the program objectives. As indicated in Table B.7, government funding for the LWF prototype effort actually exceeded the $90 million (then-year $) limit by about $23 million. Northrop and GD each received a little less than $40 million for their roles in the program. In support of Northrop's twin engine design, GE furnished seven YJ101 engines and Pratt & Whitney provided three YF100 engines for GD's YF-16 single engine models. A breakdown of government expenditures for GFAE, test evaluation, and administration appears in Table B.8, which does not include the cost of SPO personnel. Good records of SPO manning were unavailable (see Fig. B.1), but a rough estimate suggests that SPO personnel costs may have added $1 million to the costs shown in Table B.8.

Besides the government funding of the prototype program, several other costs can be identified. For instance, the two prime contractors contributed in various ways. It was reported that Northrop spent an additional $10-$15 million of its own funds on its entry.[35] On paper, it appears that GD completed its share of the program within budget; however, its two prototype aircraft were built in a separate facility that was not charged the usual corporate overhead. Moreover, GD conducted a very detailed analysis of the individual prototype aircraft parts to determine what it would cost to build similar parts for the mission aircraft with hard tooling and full scale production methods. As the RFP for the LWF prototype did not include any funding for such analyses, it presumably was covered by corporate funds.[36]

There are two lines in Table B.7 for the YJ101 engine provided by GE for the YF-17 aircraft. The engines for use in the YF-17s were funded in Project 1225. Project 1220 contained a total of $10 million to match a similar contribution by GE to complete development of the engine. It is not known if P&W contributed any corporate support for the YF-16 program.

---

[34]Belgium, Denmark, The Netherlands, and Norway.
[35]Equivalent to about $17-$25 million in FY 81 dollars.
[36]Or by Independent R&D (IR&D) funds allowed for in GD's other DoD contracts.

Table B.7

LWF/F-16 COMPETITIVE PROTOTYPE PHASE COSTS[a]
(Millions of then-year $)

Item	Fiscal Year 1972	1973	1974	1975	Total	FY 75$	FY 81$
YF-17							
Aircraft							
Airframe (Northrop)	1.5	15.3	18.8	3.5	39.1	44.0	68.6
Engines (GE)							
Project 1225	2.0	2.9	4.4	0.7	10.0	11.4	17.8
Project 1220	3.0	6.0	1.0	0.0	10.0	12.0	18.7
Total aircraft	6.5	24.2	24.2	4.2	59.1	67.4	105.1
YF-16							
Aircraft							
Airframe (GD)	1.5	14.3	18.9	3.2	37.9	42.6	66.4
Engine (P&W)	0.9	4.2	2.4	1.6	9.1	10.3	16.1
Total aircraft	2.4	18.5	21.3	4.8	47.0	52.9	82.5
Government expense[b]	0.1	1.1	1.0	5.6	7.8	8.1	12.7
Grand total	9.0	43.8	46.5	14.6	113.9	128.4	200.3
Funded	9.0	43.0	46.5	14.6	113.1	127.5	198.9

SOURCE: F-16 SPO financial records.

[a]These costs do not include $8 million (then-year dollars) spent on "transition." Although that money was spent before DSARC II, it is logically a part of the FSD program.

[b]See Table B.8 for explanation of this item.

Besides the above costs that are identified specifically with the LWF program, both Northrop and GD had substantial LWF efforts under way for several years before 1972, with some support from government study contracts but mostly with corporate funds. Finally, it is our understanding that many of the vendors, wanting to be a part of the multibillion-dollar procurement program that was expected to follow the prototype phase, sold parts at very favorable prices to assist their prime contractor to stay within his very stringent budget. For these reasons, it is not possible to determine with any precision how much was actually spent in total to design and build the four prototypes from scratch. The estimated out-of-pocket government expense for the prototype effort, however, stands at about $113 million in then-year dollars. Comparable figures in constant FY 75 and FY 81 dollars are $128 million and $199 million, respectively.

Table B.8

DISTRIBUTION OF GOVERNMENT EXPENDITURES ON NONHARDWARE ASPECTS OF THE PROGRAM
(Millions of then-year $)

Item	Fiscal Year 1972	1973	1974	1975	Total
AFFTC	.003	.022	.173	1.665	1.863
AFSWC	0	.030	.132	0	.162
AEDC	0	.295	.198	.290	.783
NASA	.065	.165	0	0	.230
GFAE	.025	.344	.054	.250	.673
Side stick pilot training	0	0	.122	0	.122
Drop model tests	0	.040	0	0	.040
MILSCRIPT	.007	.025	.015	.050	.097
Mission support	0	.086	.214	.350	.650
First destination transportation	0	.100	.114	.027	.241
Management reserve	0	0	0	2.968	2.968
Total	.100	1.107	1.022	5.600	7.829

SOURCE: F-16 SPO financial records.

Cost Estimation for the FSD Program

When the decision to put one of the two LWF prototypes in full scale development was officially approved in 1974, GD and Northrop were each given $4 million (then-year $) for a so-called "transition" effort. This money was to be used to compile data on performance and other specifications to enable the two contractors to prepare their competitive proposals for FSD. In August of 1974, requests were sent to GD and Northrop for quotations.

Northrop computed its cost estimates on a parametric basis leaning heavily on its experience with the T-38 and F-5 aircraft. GD, however, assembled its cost proposal on a part-by-part basis utilizing the data bank that had been accumulated and partially verified during its YF-16 prototype effort. The parts cost of the YF-16 had originally been estimated using a 75-element work breakdown structure and the actual costs had been tracked during the fabrication phase with a more aggregated 26-element WBS. Using that data as a starting point, GD on its own initiative had prepared analyses of what tooling, material, and labor would be required to produce the individual parts of the F-16 using MilSpecs and production methods. This was a 2½ year effort requiring the talents of about 15 people.

As a result of this part-by-part cost analysis, GD negotiators approached the FSD source selection with more than the usual amount of confidence in their cost estimates. And they knew that the aircraft design had the necessary performance because it had actually been flown.

The cost proposals arrived from the two contractors in November. These were evaluated along with the performance data and aircraft test results by an Air Force source-selection

team. In January of 1975, GD's F-16 design was selected for full scale engineering development.

Full Scale Development Contract Provisions

The full scale development contract signed with GD may seem to be in conflict with the spirit of the prototype philosophy, which calls for sequential decisionmaking after test and verification (fly before you buy). The FSD contract with GD provided for three production options to follow FSD.[37] Apparently, the purpose of this was to take advantage of the competitive situation that existed at that time. If the production contract awaited the DSARC III decision, the government would be faced with a sole source for the negotiation process. The production quantities were:

Fiscal Year	Quantity
1977	34
1978	112
1979	155
Total	301

The contract allowed for 50 percent variations in the actual quantities bought in any given year. The actual production quantities agreed upon reflect a somewhat slower buildup for USAF:

Fiscal Year	Quantity
1977	0
1978	105
1979	145
Total	250

However, because of extensive funding of long leadtime items by USAF in FY 1977 and inclusion of the Iranian buy during this period, the quantities were considered within the bounds of the options, and the prices originally negotiated were retained for these quantities. Beyond that number, the price was subject to negotiation between the government and the prime contractors.

[37]It also included an option with the EPG agreeing to build 348 aircraft for the European consortium under a fixed firm price "not to exceed" (NTE) contract. P&W also had agreed to this arrangement. The average price per aircraft established in the 1975 MOU between the U.S. government and the EPG was $6.091 million, broken down as follows (millions of 1975 $):

Airframe (NTE)	$3.450
Engine (NTE)	1.445
Radar (estimate)	0.372
GFAE (estimate)	0.153
Duplicate tooling (NTE)	0.196
Industry mgt (NTE)	0.005
FSD recoupment (NTE)	0.470
Total	6.091

The contract for full scale development of the airframe is FPIF with 90 percent of any savings going to GD and 10 percent to the government; the ceiling is 130 percent and the allowed profit (fee) is 11 percent. The USAF production contract also is FPIF, but with a 70/30 sharing arrangement and again the ceiling is 130 percent and the fee is 11 percent. The full scale development contract for the P&W F100 engine is managed by a joint office, with the F-15 SPO participating. The terms are FPIF, a 70/30 split, 120 percent ceiling, and 10 percent fee. For the engine production contract, the terms are FPIF, share ratio 70/30, ceiling 125 percent, and fee 12 percent.

Relative Importance of Prototype Costs

Table B.9 gives a breakdown of the expected total USAF funding of the F-16 program, including the procurement of 1396 F-16s,[38] full scale development, and the competitive prototype phase. When the cost of prototyping is examined in the context of an acquisition program as large as the F-16 program, its effect seems very slight indeed. Even if production had been limited to that of the USAF alone, the $113 million expenditure on the prototype phase amounts to less than 1 percent of the total then-year costs of this $19 billion program. In the context of a full multinational program of perhaps $25 billion in then-year dollars, the prototype percentage drops to slightly less than one-half of 1 percent. When we make this comparison in terms of constant dollars, these percentages increase to about 1½ percent and 1 percent, respectively. Moreover, the evidence suggests that the money spent on prototyping is not all out of pocket; there are offsetting economies in the full scale development phase. We have already mentioned the obvious carryover of certain engineering experience and perhaps some tooling from the prototype phase and that some of the tests conducted during the prototype phase may not have to be repeated during full scale development with consequent savings in fuel, personnel pay, etc.

Table B.9

F-16 TOTAL PROGRAM COSTS, INCLUDING PROTOTYPES
($ millions)

Item	Base-Year $ (FY 75)		Present-Year $ (FY 81)		Then-year $	
	$	%	$	%	$	%
Prototype	127.5	1.4	198.9	1.4	113.1	0.6
FSD	742.1	8.2	1157.7	7.9	917.8	4.9
Procurement	8193.7	90.4	13,366.6	90.8	17,794.3	94.5
Total	9063.3	100.0	14,723.2	100.0	18,825.2	100.0

SOURCES: Prototype cost: Table B.7.
FSD and procurement: F-16 SAR, September 1980.

[38]Eight FSD and 1388 production aircraft.

Originally 15 aircraft were proposed for the F-16 FSD phase. Air Force engineers later tried to estimate how many test aircraft would actually be needed in view of previous testing and the availability of the prototypes to perform some of the required FSD tests. Unfortunately, the results were too subjective to be useful. An intuitive decision was made to limit FSD aircraft to eight, primarily to reduce development costs.[39]

This reduction in test aircraft would appear to represent a cost saving at least partly attributable to existence of the prototype phase. However, estimation of the savings magnitude is difficult. In conventional acquisition programs, many of the later test aircraft are in the production configuration and are included in the development program primarily to keep the production line open until the production go-ahead is approved.[40] As Lt. General William J. Evans (then USAF Deputy Chief of Staff for Research and Development) pointed out in a 1974 appearance before a congressional committee, contractors structure their programs as much as two years in advance to provide for an orderly development program and a logical buildup of personnel, equipment, and other resources for the production phase. If there is a delay in entering production, the personnel on hand must either be paid for standing by with no work or be laid off and a new workforce then hired and trained later on. Each alternative adds to costs. Besides this, the contractors and vendors interpret delays as increased program risks, which cause price quotations to become more conservative. Of course, inflation also occurs and the program appears to cost more in then-year dollars because of stretchout.[41] In both the A-10 and F-16 prototype programs, the decision to enter production occurred before all of the FSD test results had been evaluated and the deficiencies corrected.[42] However, the remaining risks seemed within acceptable bounds and worth the gamble to permit production continuity to be maintained. Since the F-16 production startup date was advanced to cover what would have been a gap in production, there was no need to include "production" aircraft under the FSD rubric. It thus appears that most, if not all, of the seven aircraft deleted from the development contract were simply shifted to the production phase, and there was no significant net change in the overall number of F-16s acquired.

Cost Growth

The question of whether having flying prototypes upon which to base the original program cost estimates results in lower than average program cost growth will be addressed in this section. Table B.10 presents the expected cost growth of USAF's total F-16 acquisition program as projected in the September 1980 SAR. The cost figures (in millions) are shown in program base-year (FY 75) dollars, then-year dollars, and present (FY 81) values. In each case, breakouts of full scale development and procurement are shown, as well as the total for the overall program. The baseline Development Estimate is given for each group, followed by the various cost changes distributed among several descriptive "cost variance" categories. The sum of the DE and total variance equals the Current Estimate as projected in September of 1980. *Unless otherwise noted, the discussion that follows will be in terms of "real" growth, expressed in FY 81 constant dollars.*

[39]Perhaps influenced by the simpler A-10, which completed full scale development with six test aircraft in addition to the two YA-10 prototypes.

[40]For example, the F-15 program had 20 FSD aircraft but the last eight were production models (three of which were subsequently sold to Israel) that contributed only about 15 percent of the total flight-test hours.

[41]U.S. Senate House Committee on Appropriations, *Hearings Before the Subcommittee on Department of Defense Appropriations for FY 1975*, Part 7, pp. 1057-1058.

[42]For example, the F100 engine chosen for the F-16 had experienced an airborne failure in an F-15 fighter. Since the F-16 is a single engine aircraft, this was a matter of some concern.

Table B.10

F-16 PROGRAM ACQUISITION COST

($ millions)

Item	Base-Yr (FY 75) $ Cost	Base-Yr (FY 75) $ % of DE	FY 81 $ Cost	FY 81 $ % of DE	Then-Year $ Cost	Then-Year $ % of DE
Development (Quantities: DE = 8, CE = 8)						
Development estimate	578.6	100.0	902.7	100.0	659.1	100.0
Variance:						
Quantity	.0	.0	.0	.0	.0	.0
Schedule	.0	.0	.0	.0	.0	.0
Engineering	73.1	12.6	114.0	12.6	103.4	15.7
Estimating	-17.3	-3.0	-27.0	-3.0	-10.6	-1.6
Other	15.5	2.7	24.2	2.7	20.6	3.1
Support	92.2	15.9	143.8	15.9	133.6	20.3
Economic					11.7	1.8
Total variance	163.5	28.3	255.1	28.3	258.7	39.3
Current estimate	742.1	128.3	1157.7	128.3	917.8	139.3
Procurement (Quantities: DE= 650, CE = 1388)						
Development estimate	3798.2	100.0	6196.1	100.0	5395.4	100.0
Variance:						
Quantity	2946.7	77.6	4807.0	77.6	5364.7	99.4
Schedule	354.0	9.3	577.5	9.3	1434.7	26.6
Engineering	238.8	6.3	389.6	6.3	427.0	7.9
Estimating	-228.0	-6.0	-371.9	-6.0	-129.2	-2.4
Other	24.6	.6	40.1	.6	35.8	.7
Support	1059.4	27.9	1728.2	27.9	1894.3	35.1
Economic					3371.6	62.5
Total variance	4395.5	115.7	7170.5	115.7	12398.9	229.8
Current estimate	8193.7	215.7	13366.6	215.7	17794.3	329.8
Total program (Quantities: DE = 658, CE= 1396						
Development estimate	4376.8	100.0	7098.7	100.0	6054.5	100.0
Variance:						
Quantity	2946.7	67.3	4807.0	67.7	5364.7	88.6
Schedule	354.0	8.1	577.5	8.1	1434.7	23.7
Engineering	311.9	7.1	503.6	7.1	530.4	8.8
Estimating	-245.3	-5.6	-398.9	-5.6	-139.8	-2.3
Other	40.1	.9	64.3	.9	56.4	.9
Support	1151.6	26.3	1872.1	26.4	2027.9	33.5
Economic					3383.3	55.9
Total variance	4559.0	104.2	7425.5	104.6	12657.6	209.1
Current estimate	8935.8	204.2	14524.3	204.6	18712.1	309.1

SOURCE: September 1980 SAR.

Development Cost

The amount of cost growth in the development phase, 28 percent, is somewhat better than that of most of the nonprototype "mature" programs that were examined in an earlier Rand study of military acquisition,[43] but it is higher than the growth for the other prototype programs described in this appendix. However, in contrast to the other prototype programs, the cost of the F-16 prototype phase is excluded from the SAR tabulations. Therefore, the F-16's DE baseline estimate is a true projection—it does not contain any past (and therefore known) costs. As such, for comparing the accuracy of cost projections, this F-16 development cost growth percentage is comparable to the A-10's adjusted growth figure of 35 percent.

The original F-16 estimate for development was increased by 13 percent primarily to cover the addition of the nuclear role, a radar warning receiver, and some engine reliability improvements that were found to be necessary because of problems that surfaced after FSD began. More than half of the increase in the development phase falls into the Support category. The original F-16 support equipment estimate was made with a cost estimating relationship based on previous Air Force programs that did not have a sophisticated automated avionics test facility. Such equipment was not used during the evaluation of the prototype aircraft and it was not foreseen at the time the DE was prepared. In the context of the F-16 program as a whole, these development cost increases are of minor importance.

Procurement Cost

Procurement costs of the F-16 program more than doubled, but as is clear from the Quantity line of Table B.10, the DE represented 650 aircraft whereas the CE represents more than double that number. Total procurement costs, of course, tend to scale with the number of units produced, and it would be misleading to compare the cost growth of programs that held production quantities constant with others that did not. For this reason, we have attempted to normalize the cost growth experienced by the F-16 program for the baseline quantity that underlies its original Development Estimate.

A rough quantity cost correction can be made by simply deleting the Quantity variance, which in the F-16 program accounts for two thirds of the total increase in the procurement phase. However, Quantity variance only accounts for the increases attributed to the aircraft itself. There also was a significant increase in the ground-support equipment associated with this increase, but its cost is included in the aggregative Support category. Moreover, any cost growth subsequent to the change in quantity is in terms of the new aircraft number and, in this program, is about double the amount that would correspond to the baseline quantity.

Table B.11 illustrates the method that was used to adjust the total procurement cost growth, shown in Table B.10, to represent the baseline quantity. Aircraft flyaway cost growth was adjusted somewhat differently than that of the support elements. For each group, the cost changes that were approved before the quantity increase were summed with the original DE to establish the estimated total cost of the baseline number of aircraft up to that point. Cost growth following the quantity change was then identified and converted into baseline-quantity terms. For the support group, we simply scaled (650/1388) the cost growth that followed the quantity change to correspond to the smaller baseline quantity. The aircraft flyaway cost adjustment, however, also attempts to account for learning curve effects. We computed the

[43] Dews et al., Table 6.

Table B.11

F-16 PROCUREMENT COST GROWTH, NORMALIZED FOR BASELINE QUANTITY[a]

($ millions)

Item	Aircraft Quantity	Total Program[b] Cost (FY 75 $) Total	Total Program[b] Cost (FY 75 $) $/Acft	Normalized for 650 Aircraft Cost (FY 75 $) Total	Normalized for 650 Aircraft Cost (FY 75 $) $/Acft	Normalized for 650 Aircraft Cost (FY 81 $) Total	Normalized for 650 Aircraft Cost (FY 81 $) $/Acft	% of DE
Total development estimate	650	3798.2	5.843	3798.2	5.843	6196.1	9.532	(100.0)
Flyaway								
Development estimate	650	3031.7	4.664	3031.7	4.664	4945.7	7.609	100.0
Variance								
Before quantity increase	650	167.1		167.1	0.257	272.6	0.419	
Quantity increase	+738	2946.7						
Subsequent								
Aircraft	1388	222.3		116.0	0.178	189.2	0.291	
"Support"[c]		123.7		58.0	0.089	94.6	0.146	
Total variance		3459.8		341.1	0.524	556.4	0.856	11.2
Current estimate	1388	6491.5	4.677	3372.8	5.188	5502.1	8.465	111.2
Other								
Development estimate	650	766.5	1.179	766.5	1.179	1250.4	1.924	100.0
Variance								
Before quantity increase		330.3		330.3	0.508	538.8	0.829	
Quantity increase		567.7						
Subsequent								
Support		161.4		76.0	0.117	124.0	0.191	
Less "flyaway"[c]		-123.7		-58.0	-0.089	-94.6	-0.146	
Total variance		935.7		348.3	0.536	568.2	0.874	45.4
Current estimate	1388	1702.2	1.226	1114.8	1.715	1818.6	2.798	145.4
Total variance		4395.5		689.4	1.061	1124.6	1.730	(18.2)
Total current estimate	1388	8193.7	5.903	4487.6	6.904	7320.7	11.263	(118.2)

[a]Figures rounded after calculations.
[b]F-16 SARs various dates--most recent was September 1980.
[c]This amount of flyaway cost is included as Support in variance analysis section of SAR.

implied slope of the learning curve by correlating the cumulative average cost per aircraft just before the quantity increase, for 650 aircraft, with that of the increased number, based on the incremental cost given in the SAR Quantity variance category for the 738-aircraft add-on.

European coproduction in the F-16 program added a complication to this method. U.S. firms produce components for a portion of the EPG aircraft and the European producers make parts for USAF's initial 650-aircraft program. As a rough rule of thumb, the F-16 SPO estimates that the net effect of this shared production is equivalent to 144 additional aircraft produced by the U.S. contractors. Therefore, in calculating the curve slope we assumed the additional 738 aircraft would begin at unit 803 (following 8 R&D, 650 USAF program, and

144 coproduction equivalent aircraft). This calculation resulted in a curve slope estimate of between 86 and 87 percent.

In view of the expected increase in efficiency due to the all-U.S. production of the additional aircraft, and the inclusion of nonrecurring costs in the first part of the program, this slope may seem a bit conservative. However, the coproduction equivalent aircraft adjustment was only an approximation, and the curve for the F100 engine—used in common with the F-15 fighter—must be quite flat. From a practical standpoint, in the quantity range under consideration, and given the small amount of subsequent cost variance being adjusted, the normalization is not very sensitive to the curve choice over a fairly wide range.

One further minor adjustment was required in Table B.11. The flyaway cost figure shown in the Financial Summary of the SAR includes $123.7 million of the cost increase that in the Variance Analysis section of the SAR is attributed to Support. The equivalent of this amount was transferred to the flyaway group after the quantity adjustment calculations were made.

The above normalization method is intended to account for cost growth that occurs throughout the entire acquisition program; it is not limited to growth during the production of the first 650 F-16s. It includes a proportional share of the cost increase that will be generated by the production rate reduction planned for the second half of the program. There may be some overstatement of growth because of the implicit assumption that all of the cost changes following the quantity increase vary directly with the magnitude of the quantity change. In fact, some minor proportion of the cost changes may be nonrecurring and theoretically should be allocated entirely to the baseline total—e.g., new tooling associated with engineering changes and one-time renegotiation costs associated with changes in production rate. An opposite bias is introduced by assuming that all of the post-quantity cost growth is based on 1388 aircraft, ignoring the probability that for already-produced aircraft, the cost of some of these changes will be financed from the modification budget. The quantity adjustment method described above admittedly is imprecise, but it is believed to provide an approximation of normalized cost growth that is adequate for the purposes of this study.

The normalized amount of cost growth in F-16 procurement is 11 percent for the flyaway category alone and 18 percent overall. The F-16 SAR states that this program no longer has a DTC goal, but at the 650 quantity, and assuming a 15 aircraft per month production rate, the flyaway cost growth would amount to only 5 percent—a remarkable achievement. The multinational agreement contributed to the F-16's fairly low cost growth during the first half of the program by enabling it to avoid the stretchouts that have plagued other military acquisition programs. However, as was mentioned earlier, a cut in the production rate to 10 aircraft per month is planned for the beginning of the second (all-U.S.) part of the program and that adds about five percentage points to the F-16's normalized procurement cost growth. The other noteworthy increases, shown in the Engineering and Support categories, correspond to the program changes identified earlier, in the discussion of the development phase. These increases in program scope were offset to a small extent by the apparently over-conservative cost estimates for the F-16 program as originally conceived.

Cost Growth Summary

Table B.12 summarizes the F-16 development, procurement, and total program normalized cost growth. The 28 percent growth in the development phase is almost 60 percent higher than the adjusted procurement increase but because of the small dollar magnitude of develop-

Table B.12

F-16 PROGRAM COST GROWTH, NORMALIZED FOR BASELINE QUANTITY[a]

($ millions)

	Total Program[b]			Normalized for 658 Aircraft					
		Cost (FY 75 $)			Cost (FY 75 $)		Cost (FY 81 $)		
Item	Aircraft Quantity	Total	$/Acft	Aircraft Quantity	Total	$/Acft	Total	$/Acft	% of DE
Development									
DE	8	578.6		8	578.6		902.7		100.0
Variance		163.5			163.5		255.1		28.3
CE	8	742.1		8	742.1		1157.7		128.3
Procurement									
DE	650	3798.2	5.843	650	3798.2	5.843	6196.1	9.532	100.0
Variance		4395.5			689.4	1.061	1124.6	1.730	18.2
CE	1388	8193.7	5.903	650	4487.6	6.904	7320.7	11.263	118.2
Total program									
DE	658	4376.8	6.652	658	4376.8	6.652	7098.7	10.788	100.0
Variance		4559.0			852.9	1.296	1379.7	2.097	19.4
CE	1396	8935.8	6.401	658	5229.7	7.948	8478.4	12.885	119.4

[a]Figures rounded after calculations.
[b]F-16 SAR, September 1980.

ment total costs, it had little discernible effect on the overall program rate: one percentage point above the procurement cost growth described earlier.

From these favorable results, one might conclude that the existence of a flying prototype aircraft enabled the estimators to produce a more reliable projection of total program costs. Despite the unforeseen engine problem, this program does seem to have been able to meet its original performance specifications with few engineering changes. However, the estimators did not foresee the introduction of the automatic test equipment or the improved performance later demanded of the F-16. The existence of a prototype aircraft also was of no use in predicting one of the primary causes for the F-16's cost increase—the reduction in production rate. Finally, although the Estimating variance, being negative, has contributed to a reduction in the F-16 program's overall cost growth, it nonetheless represents errors in an absolute sense; and its magnitude is no better than average for all of the aircraft programs examined in this study.

Appendix C

UTILITY TACTICAL TRANSPORT AIRCRAFT PROTOTYPE PROGRAM[1]

BACKGROUND

In its Utility Tactical Transport Aircraft System (UTTAS) project, the Army used prototypes to pursue rather unusual developmental goals. Although the RFP that appeared in January of 1972 demanded better performance than the Army had obtained from its UH-1 ("Huey") helicopter, more important than performance was the aircraft's lifetime cost, a figure powerfully influenced by its reliability, availability and maintainability. Whatever other features the service wanted in its new utility helicopter, it sought above all to enhance the aircraft's RAM performance.

To do this, the Army structured the UTTAS development project in an unusual way. Believing that reliable RAM statistics could be generated only by using full scale production prototypes, and believing as well that the aircraft's performance requirements could be met with available, low-risk technology, the service initiated the program as a full scale development from the start; the UTTAS prototype program thus commenced with DSARC II and ended with a production decision. In an effort to generate statistically significant RAM figures before making a production commitment, the service hoped to take *six* full scale development prototypes from each of two competing contractors through a grand total of 11,360 flight test hours. Although the Army's original plans were modified by the Senate Armed Services Committee, the somewhat curtailed program finally approved by the Congress still involved several thousand hours of aircraft and engine testing over a period of two years.

Although the RFP that formally launched the UTTAS development project appeared in January 1972, the project began in October 1965, when OSD approved an Army Qualitative Materiel Development Objective for a new utility helicopter. Over the intervening six years the service debated both the wisdom of initiating the development of a new utility helicopter and the goals such a development program should pursue. It finally resolved this debate in favor of a new aircraft that would be capable of carrying a fully equipped infantry squad, an aircraft that it hoped would be more survivable and reliable, and require less maintenance, than any helicopter then available.

During the late 1960s the Army formulated the goals of a prospective utility helicopter development program with tradeoff analyses covering many aspects of utility helicopter performance. The war in Vietnam provided useful data for these analyses, and the Army's experience there helped it define its operational needs in a utility aircraft. Beyond battlefield experience and information, the Army tasked potential contractors such as Boeing Vertol, Sikorsky, Bell, Lycoming, and GE with tradeoff studies. Although many of these were "paper analyses," others involved limited hardware development. In response to debate over the optimal size of a new helicopter, for example, Boeing Vertol constructed mockups of aircraft with various dimensions for demonstration purposes. According to the Deputy Program Manager for the UTTAS project, these studies greatly aided the service when it finally began to formulate the project's RFP.

[1]Geraldine Walter assisted in the preparation of this case study.

By far the most critical information generated during this period came out of the Army's "demonstrator engine program," launched in 1967. Drawing upon analysis conducted in Army laboratories, the Army's Aviation Systems Command[2] published a brief RFP for a helicopter engine of considerably higher performance than anything then available. In particular, the RFP demanded high power—1500 shp—at the low weight of 400 pounds. In addition, it asked contractors to pay attention to reliability and maintainability as well as the engine's producibility. General Electric and Pratt and Whitney won contracts for the demonstrator program.

Over the summer and fall of 1971 AVSCOM took the findings of this demonstrator program and wrote a formal RFP for what would become the T700 engine. Again, GE and Pratt and Whitney competed for this project, with GE emerging the winner. The GE design, which promised a power-to-weight ratio twice that of the Huey's engine, was modularized and included special particle separators designed to keep dust out of the engine's interior. Although the engine development contract with GE was not made final until March of 1972, the Army announced GE's victory late in 1971.

By the time the T700 RFP was published, the UTTAS program had also been approved. The timing here was not accidental, for the demonstrator engine program solved the major uncertainties associated with the development of a new utility helicopter. Specifically, it demonstrated that much higher engine performance was possible than had been achieved in the past and that stressing reliability, availability, and maintainability in the design of a piece of equipment could lead to greatly improved RAM performance in the finished product. Only after the T700 program was approved did it become clear that the service would initiate a "ground-up" development project for the new aircraft. In fact, the Army specifically designated the T700 as the UTTAS engine, and funding for subsequent development of that engine was carried on the UTTAS program's budget.

After having considered aircraft of widely varying sizes, by late in 1971 the service settled on one that would carry a fully equipped infantry squad (11 men at an average of 240 pounds each) in addition to its crew and door-gunners. Because the UH-1 at best had carried six or eight soldiers, the service saw a need for a UTTAS fleet about two-thirds the size of its Huey fleet.

The underlying purpose of the new program was to achieve lower fleet life-cycle costs by stressing high RAM performance in its prototype aircraft. Army witnesses before the Congress testified that the UTTAS fleet would offer lifetime costs less than half those associated with a comparable (hence larger) fleet of Hueys.[3] Because RAM performance over the life of a helicopter strongly influenced its life-cycle cost, the service placed its hopes for such reduced costs primarily on the achievement of greatly improving the RAM performance of its new aircraft over that of the UH-1. The Army proposal for a UTTAS program went before the DSARC in May 1971, the same month in which the engine RFP went to contractors, and the UTTAS RFP appeared in January 1972.

THE UTTAS RFP AND PROGRAM STRUCTURE

The Army's goal of validating the RAM performance of its new utility helicopter before it decided to produce the aircraft influenced nearly every aspect of the UTTAS RFP. That

[2]In 1977 AVSCOM became AVRADCOM—the Aviation Research and Development Command.

[3]U.S. Senate, Committee on Armed Services, *FY 1973 Authorization for Military Procurement*, Hearings, 92d Cong., 2d Sess., Part 4, p. 2209.

750-page document defined in some detail not only what the service wanted by way of performance, but also how the service wanted to achieve high levels of reliability and availability (which, under combat conditions, amount collectively to "survivability"). More important, the UTTAS RFP outlined a program structure designed to allow the service to test extensively the RAM performance of its prospective UTTAS.

Behind the RFP lay the basic assumption that RAM performance could be tested only on fully developed aircraft. Thus the service structured the UTTAS program as a full scale development effort; DSARCs I and II coincided with the day the program began. The RFP included not only the basic performance requirements outlined in Table C.1, but MilSpecs and other detailed design criteria, together with requirements for elaborate contractor reporting.

The emphasis on RAM also can be seen in the requirement itself. Major performance parameters, such as speed, rate of climb, and so forth, were given in bands of acceptable performance. This presumably allowed contractors freedom to trade performance for lower cost in an effort to stay within the RFP's stated DTC goal of $951,000 unit flyaway cost (FY 72 dollars, 1107 airframes, 4700 engines, 14 aircraft per month).[4] By contrast, RAM goals took the form of specific targets, an indication that in these areas the service would accept tradeoffs only reluctantly, if at all. In addition, the UTTAS RFP defined what it wanted quite precisely by demanding triple-redundant secure communications within the aircraft, two engines rather than one, double-redundant oil lines, self-sealing fuel lines, and the like.

Given that the program lacked an advanced development phase, the service sought to confine the UTTAS requirement to the "low risk" area. A utility helicopter had never before achieved the performance demanded of UTTAS prototypes, but the Army believed the UTTAS requirement could be met through the use of demonstrated technologies that, although available, had not been combined in one aircraft.

Although the service sought to use competition in the UTTAS program, the length and detail of the UTTAS RFP make clear that it did *not* do so in an effort to run an austere, highly flexible development project. Rather, it was to ensure that contractors would keep their eyes focused on the RAM performance of their prototypes. As the first UTTAS project manager told the Senate Armed Services Committee in 1972, "my position is that we should have a competitive development. . . . I think that we will get more attention to our problem of reliability and maintainability."[5] Thus the UTTAS program called for two contractors to compete through the length of a full scale development effort to a production decision, and source selection thus served to initiate maturity testing, tool-up for and the beginning of low rate production.

Perhaps the most striking aspect of the program's structure was the amount of testing the Army envisioned. To be certain that it chose the prototype offering higher RAM potential, the service designed a program that "through the use of additional prototypes and a very heavy degree of operational testing" generated RAM data voluminous enough to provide high

---

[4]Department of Defense, *Selected Acquisition Report: Black Hawk*, 3 July 1979, p. 7. Design-to-cost considerations appear to have come late to the UTTAS program. There is no mention of a program DTC goal in the FY 1973 hearings that covered the program, for example; at that point $600,000 was mentioned as a cost estimate for the airframe. Later this figure became the design-to-cost goal, but was not presented with an associated production rate and total buy. Interviews reinforced the impression that DTC considerations had not been part of the service's original thinking on the program, but instead were introduced by OSD as the program got under way. See U.S. Senate, Committee on Armed Services, *FY 1975 Authorization for Military Procurement*, Hearings, 93d Cong., 2d Sess., Part 5, p. 2616, for an early and rather vague reference to the program's DTC goal.

[5]U.S. Senate, Committee on Armed Services, *FY 1973 Authorization for Military Procurement*, Hearings, 92d Cong., 2d Sess., Part 4, p. 2222.

Table C.1

MAJOR UTTAS PERFORMANCE GOALS
(95% maximum rated power, 95° F, mission gross weight)

Performance	UTTAS	UH-1H
Hover out of ground effect	4000 feet	Sea level (max. power)
Vertical rate of climb (4000 feet altitude, 0 airspeed)	450-650 fpm	--
Speed	145-175 kn	105 kn
Payload (4000 feet above sea level, mission fuel)	11 troops	(?) 1 troop
Endurance (mission fuel)	2.3 hr	2.1 hr
MMH/FH (unscheduled)	3.8	6.7
Availability	82%	75%
Air transportability[a]	6.5 hr	38.5 hr
Vulnerability	7.62mm	7.62mm
	direct hits	(pilot protection only)
Vibration level	.05 g	.25 g

SOURCE: U.S. Senate, Committee on Armed Services, FY 1973 Authorization for Military Procurement, Hearings, 92d Cong., 2d Sess., Part 4, p. 2201.

[a] Time required to prepare aircraft for transport aboard C-130 or C-141.

confidence in the RAM statistics finally obtained.[6] The Army initially proposed the development of 14 prototypes; six flying aircraft and one ground test vehicle from each of two contractors. (Plans also called for the construction of one structural test vehicle, complete with T700 engines, which the service did not call a prototype.)[7] Contractor tests were

[6] See the testimony of General Maddox, then Chief of Army Aviation, in U.S. Senate, Committee on Armed Services, *FY 1974 Authorization for Military Procurement*, Hearings, 93d Cong., 1st Sess., Part 4, p. 4792.

[7] See the arguments on the numbers issue between Army representatives and Senator Thomas McIntyre, in U.S. Senate, Committee on Armed Services, *FY 1973 Authorization for Military Procurement*, Hearings, 92d Cong., 2d Sess., pp. 2217ff, and U.S. Senate, Committee on Armed Services, *FY 1974 Authorization for Military Procurement*, Hearings, 93d Cong., 1st Sess., pp. 2018ff. See also General Maddox's published reply to McIntyre's criticism, "A Rebuttal on UTTAS," *Government Executive*, June 1972, pp. 44-50.

expected to take over a year, after which Government Competitive Testing would run for yet another nine months. Nearly two years of tests would net a total of 11,360 flight hours on all aircraft. And with two engines per aircraft, total engine test hours would be 22,720, a number AVSCOM felt was sufficiently large to give it about 95 percent confidence in the RAM data collected during test and evaluation.[8]

In presenting the project to the Congress in 1972, Army representatives projected the schedule shown in Table C.2. In the year after its initiation, the UTTAS program structure came under heavy fire from Thomas McIntyre, chairman of the R&D subcommittee of the Senate Armed Services Committee. McIntyre argued that the program as the Army had structured it constituted "two simultaneous full-scale weapon system developments for a weapon system which has been described previously . . . as low risk." Hence, it appeared to be "an extreme example of unwarranted duplication."[9]

Table C.2

PROJECTED UTTAS PROGRAM MILESTONES

Event	Date	Months
RFP publication	1/72	
Contract award	9/72	9
First flight	9/74	33
Flyoff begins	9/75	45
Flyoff ends	9/76	57
First production aircraft accepted	8/78	80

SOURCE: U.S. Senate, Committee on Armed Services, FY 1973 Authorization for Military Procurement, Hearings, 92d Cong., 2d Sess., Part 4, p. 2201.

In a letter to Secretary of Defense Melvin Laird written just a month after AVSCOM published the UTTAS RFP, McIntyre proposed an alternative approach:[10]

1. Reduce the number of prototypes for each contractor from seven to four, which would provide each contractor with one ground test prototype vehicle, one contractor retain flying prototype, and two government evaluation prototypes.
2. Reduce the number of spare engines consistent with the reduction in the number of prototypes.
3. Reduce the number of flying hours . . . to that quantity necessary solely for the purpose of conducting tests through the competitive flyoff to permit the selection of one contractor.

[8]U.S. Senate, Committee on Armed Services, *FY 1973 Authorization for Military Procurement*, Hearings, 92d Cong., 2d Sess., Part 4, p. 2217.
[9]U.S. Senate, Committee on Armed Services, *FY 1974 Authorization for Military Procurement*, Hearings, 93d Cong., 1st Sess., Part 4, p. 2042.
[10]Ibid., pp. 2052-2053.

4. Proceed on the basis that the winning contractor would be granted an engineering development contract to complete the necessary refinements in development and testing, including accommodation of maintainability and reliability objectives leading to a production decision.

McIntyre made the proposal with the F-16 and A-10 programs in mind and in part asked the Army to explain why its program involved so many more prototypes and so much more time than "comparable" Air Force programs. His directive sought to shape the UTTAS development along lines similar to the F-16 and A-10 programs.

In replying to McIntyre's letter for the service, Deputy Secretary of Defense Kenneth Rush wrote that

> (r)eduction of prototypes or test hours substantially could jeopardize important developmental goals at relatively small savings of R&D funds Meaningful reliability and maintainability testing requires high statistical sampling under realistic conditions.

The UTTAS program, Rush continued, had different goals than the F-16 or A-10 program, and "differing purposes determine their structure." Since the UTTAS program was "oriented towards fulfilling a well-established requirement with the costs of acquisition and operations a most important consideration," it deserved to retain its special form.

Notwithstanding the reply, the Congress cut the UTTAS program's FY 74 budget and forced the service to reduce the number of flying prototypes from 12 to six. In testimony before McIntyre's subcommittee during the FY 74 budget hearings, the Army sought without success a compromise program that involved 12 prototypes, with five instead of six flying aircraft. Each contractor ultimately fielded three flying prototypes.

But if the number of prototypes changed, the structure and goals of the UTTAS program did not. It remained a competitive, full scale development with enhanced RAM as its central goal. With only six flying prototypes the service could not establish the high confidence data base it once had sought. Rather than change the program, the Army restructured the UTTAS test schedule to optimize flight hours relevant to determining RAM performance. Avionics testing, for example, was moved to the maturity phase of the program (post-DSARC III) to permit more time for operational flight tests.

MANAGING THE PROGRAM

The length and detail of the UTTAS RFP was matched by an equally lengthy and detailed set of reporting requirements levied on contractors from the start of the project. Concerned with the performance of its new aircraft, convinced of the low risk of the project, and working in any case toward a production decision, the Army PMO managed the UTTAS project in an inflexible and carefully controlled manner. To be sure, the UTTAS RFP stated major performance requirements (less those associated with RAM) in the form of bands. Given that the project had a design-to-cost goal associated with it, these bands were essential to give the contractors the freedom required to trade performance for savings where necessary. As an Army witness told members of the Senate Armed Services Committee in 1974, "The contracts contain these performance bands which allows [sic] the contractors sufficient design flexibility to permit trade offs and remain at or below their design to cost goal."[11]

[11]U.S. Senate, Committee on Armed Services, *FY 1975 Authorization for Military Procurement*, Hearings, 93d Cong 2d Sess., Part 5, p. 2602.

Despite such flexibility, the RFP as a whole pushed contractors to the limits of what was technically feasible. Barely able to meet the overall requirement, contractors could hardly take advantage of the "freedom" permitted by the RFP's performance bands. For example, a band like that specifying vertical rate of climb—450 to 650 fpm—interpolates to a range of only $\pm \frac{1}{2}$ percent in power requirements. The seemingly broad performance bands in the RFP thus masked extremely tight bands on *important* tradeoffs. Furthermore, the contractors were held tightly to the specifications and performance requirements contained in the UTTAS RFP.

Competition, together with the Army's inflexibility, forced the contractors to face cost issues earlier in the program than either probably would have done under other circumstances. Early in the development phase, both firms created costing teams that met with designers and engineers as they designed the original prototypes. At such meetings the cost experts forced the designers to consider the cost as well as the performance of the component they were designing. Personnel at both firms can point to examples in which this process netted real savings. They suggest that the process also gave the Army's PMO a much better grip than normally would have been the case on the validity of cost estimates quoted in production proposals submitted at the end of the project's test and evaluation phase.

If the Army PMO denied contractors much flexibility in meeting the UTTAS requirement, it also denied them the freedom to pursue the development of their prototypes on their own. The UTTAS RFP's reporting requirements called for monthly "vulnerability status reports," as well as monthly (later, biweekly) weight projections and cost estimates. It required contractors to submit all test flight proposals to the PMO for approval, and it specified major design-to-cost review audits at 15, 24 and 30 months into the program's life. From the start, members of the PMO made it clear to contractors that they intended to exploit these managerial controls to the fullest.

In part this stress on close supervisory control stemmed from the project's goals and structure; this was a full scale development leading directly to production, and members of the UTTAS project office sought to ensure that every detail received their attention. The stress on supervision also may have resulted from the Army experience with the Cheyenne development. Army acquisition personnel blamed the Cheyenne's problems in part on the *lack* of service control over that project and did not intend to let that happen again. Although there was competition in the UTTAS project, they sought to control the program carefully from start to finish.

Sikorsky's project manager and his associates argue that these managerial practices cost the Army little. AVSCOM's technical personnel quickly grasped the nature of emerging technical problems and worked overtime to assess each contractor's proposed solutions as rapidly as possible. It took AVSCOM a month, for example, to evaluate Sikorsky's proposal to lengthen the rotor shaft of its prototype in response to vibration problems encountered during initial tests.

Boeing Vertol personnel are less sanguine about the efficacy of the Army's managerial approach. In several cases, they argue, the UTTAS RFP demanded figures that could at best be specified only late in the program's life. How can engineers firmly estimate weight in the initial design stages, for example? Indeed, AVSCOM itself had problems on this score; the weight estimate on which it parametrically computed the project's DTC target fell short of the final weight of either firm's prototype. The same uncertainty applied to costs. Progress reports came every three months—far too often, many felt, to be meaningful. And the cost reporting requirements engaged 20 plant personnel full-time.

Whatever the degree of PMO oversight and control, the UTTAS PMO actually fielded

and tested prototypes more rapidly than seems to be the case with commercial helicopter design. As vibration machines, helicopters pose severe design problems that resist analysis on paper or on the basis of wind tunnel tests. Vertol normally took 32 months to take a proposal from design to first flight and some 18 to 19 months for initial testing. Sikorsky and Hughes Helicopters produced similar figures. In allowing contractors 24 months from contract award to first flight, and 16 to 17 months for initial testing, the UTTAS PMO clearly pushed contractors very hard. The project nonetheless stayed close to this schedule, suggesting that the Army's tight management control of the project did not slow it down unduly.

BUILDING THE PROTOTYPES

Three contractors responded to the UTTAS RFP when it appeared in January of 1972. Bell offered two proposals, each of which took exception to stated requirements, and neither of which was seriously considered. Sikorsky made one bid, based on the conservative winner of the firm's pre-RFP design competition. Boeing Vertol submitted a conservative and a slightly more risky proposal, both promising higher risks than the Sikorsky design. Given the RFP's length and detail, these proposals were themselves rather long; Vertol's bids came to about 4000 pages plus drawings. Consequently, it took AVSCOM six months to evaluate responses. Late in August of 1972 AVSCOM awarded Sikorsky and Boeing Vertol CPIF contracts for a competitive development effort to extend over the next 26 months, followed by some two years of test and evaluation.

To meet the UTTAS requirements, each contractor innovated, very carefully, in two senses. First, each incorporated into its UTTAS design the best of the tried and tested technologies available on other in-house helicopter designs. Each basic technology, in other words, came to the UTTAS from a trial period on some other design, yet never before had the "best of everything" been installed on one aircraft. Second, each contractor paid careful attention to RAM criteria, to the point of sacrificing a certain amount of technical elegance to ease of maintenance and repair.

The Sikorsky Prototype

As a firm with a reputation for conservative design, Sikorsky not surprisingly chose the tried-and-true fully articulated rotor system for its UTTAS candidate, dubbed the UH-60A. Still, the firm's rotor design used state-of-the-art[12] design features. Prime among these were its elastomeric rotor bearings, made of alternating shims of rubber and steel. These, it was hoped, would be maintenance free, with a promised useful life of some 2500 hours, several times that of more conventional rotor bearings. Sikorsky had tested the elastomeric concept of its CH-53 helicopter, and improved that design slightly as it moved to the UH-60A.

From its CH-53 the firm also borrowed the basic design for the UH-60A's titanium rotor spar.[13] Running the length of each rotor blade, this spar's strength relative to the aluminum spars normally used permitted engineers to enhance both the spanwise and chordwise lift of

[12]The phrase comes from Warren C. Wetmore's "Reliability Emphasized in UH-60 Design," *Aviation Week & Space Technology*, April 11, 1977, p. 42. See that article for the best publicly available summary of the technical options Sikorsky used.

[13]Ibid., for technical data on the blade; and Peter Arcidiacono and Robert Zincone, "Titanium UTTAS Main Rotor Blade," *Journal of the American Helicopter Society*, April 1976, pp. 12-19.

the helicopter's rotor blades. Aluminum spars accept a maximum twist of about 6°, and the titanium spars used on the UH-60A permit an 18° twist. Hence, the UH-60A's rotor blades can rotate faster than blades with aluminum spars, generate more lift, and have an enhanced spanwise lift distribution.

Because the UH-60A's blades rotate faster than those of older helicopters, the blade tips encounter compressibility problems associated with supersonic flight. On the S67 gunship prototype Sikorsky fielded in 1972, the firm had first tested the notion of sweeping the rotor blade's tip, for much the same reason that the wings of a high-speed aircraft are swept. It carried the idea over into its UH-60A design.

Sikorsky also used new and interesting design features to solve survivability and transportability RAM problems. By canting the tail rotor of its UH-60A upward slightly, for example, Sikorsky obtained lift forces as well as lateral forces from this rotor. This moved the aircraft's center of gravity forward, which in turn allowed designers to shorten the helicopter and thereby facilitate its transport in a C-141A.

To enhance the aircraft's survivability, Sikorsky's designers placed the tail rotor on the right of the tail pylon, even though in this position it forces air against the pylon itself. In this location, the tail rotor, if hit and separated from the aircraft, will fly *away* from the tail pylon rather than into it. Although the firm has had to adjust its tail design to compensate for the forces so created, its engineers consider it worth sacrificing a certain amount of design elegance from the aerodynamic point of view to achieve increased survivability.

Several other design features improved the aircraft's survivability. On the assumption that a grease line hit by ground fire will not leak like one carrying oil, for example, Sikorsky's engineers sought to replace the oil lubrication system typically used in helicopters with a grease system. They also mounted the UH-60A's engines behind main structural members and ran most wires and tubes alongside such members. The UH-60A's cabin structure is designed to resist "parallelogram" deformation under heavy inertial loads, and both landing gear and crew seats are designed to absorb the shock of rapid vertical deceleration. Finally, fuel lines are self-sealing and are connected with breakaway fittings to prevent fuel leakage and fire in the event of a crash.

Some of the UH-60A's more interesting RAM design features include high degrees of modularization and right-left interchangeability. Both the transmission and rotor head are modularized (as is the engine, though the T700 is not of Sikorsky design); if one component fails, its module can be replaced quickly, without removing the entire apparatus. Moreover, transmission modules are right-left interchangeable, as are the aircraft's doors, landing gear, engine cowlings, fuel tanks and several other parts. Parts should be easier to obtain in the field, especially from damaged and inoperable aircraft.

Also to enhance RAM performance, the original Sikorsky design included a fluidic stability augmentation system. Coupling the pilot's control sticks and the aircraft's rotor, this device smooths vibrations inherent in the rotor's motion before they reach the controls. Sikorsky's designers, aware that Diamond Labs had been perfecting a fluidic system with no moving parts and hence of potentially high reliability, designed a fluidic system for their UTTAS candidate.

Sikorsky's first UTTAS prototype flew on October 17, 1974, 26 months after the firm had won its UTTAS contract and about 40 months after the firm's design team had set out to design a candidate based on its anticipation of the Army's RFP. By the time Government Competitive Tests began, the UH-60A had already undergone several design iterations.

Boeing Vertol's Prototype

Like Sikorsky, Boeing Vertol used what it felt was the best of what was available at reasonably low risk to field its UTTAS prototypes. Vertol's basic UTTAS design choice, and the one that moved its prototype into a slightly higher risk category than Sikorsky's UH-60A, was the semi-rigid rotor/fiberglass rotor blade on which the firm based its design. In this rotor system, the glass fibers of the rotor blade's core run in an elongated U from the tip of the rotor blade into and around a retainer pin in the hub and back out to the end of the spar. Lag and flap movements simply flex the fiberglass blade root, and the blade retainer pin is part of a hinge for pitch articulation, hence the term "semi-rigid." Although semi-rigid systems are fairly new, Vertol had used such a system, along with the fiberglass blade, on its BO.105, a four-passenger helicopter built during the 1960s under license from the German firm MBB.[14]

Vertol chose this design to enhance performance, RAM, and survivability. "The combination of glass fiber rotor blades and a hingeless rotor hub," the firm's director of engineering wrote in 1975, "yields rapid, sensitive, rate control characteristics essential for . . . conducting nap-of-the-earth . . . operations." Control input response, he continued, "is obtained in less than 0.4 seconds compared to at least 2.0 seconds characteristic of teetering and articulated rotor systems."[15] Further, because it has no lag or flap hinges, the semi-rigid rotor system is simpler than fully articulated systems and promises reduced maintenance and repair costs. Finally, because a break in one glass fiber rarely extends to contiguous fibers (as does a widening crack in metal blades), the blade root as well as the blade itself resists cracking and shattering under ballistic impact. Ground fire that hits a blade will leave its mark while the rest of the blade retains its strength, "preventing loss of aircraft and allowing completion of mission."[16] Although some of the system's promise has yet to be realized, Vertol had more experience with it than did any other helicopter firm and felt reasonably confident in using it on the UH-61A.

For the same reasons the firm used a hingeless tail rotor as well. And again, this system had been tried—in smaller scale and to less demanding requirements—on the BO.105.

Vertol's program managers concerned themselves with RAM from the very beginning of the design phase. They created a RAM team, totally independent from the project's design and engineering staff, to do nothing but draw attention to RAM issues. Often this team simply took engineering drawings and built cardboard mockups to scale. From these, engineers could get a feel for parts accessibility. Like the design-to-cost teams used by both firms, the RAM team created a "corporate conscience," which persistently "nagged" about RAM criteria.

The team's effort produced results. The UH-61A's tail stabilizer, for example, was finally located directly under the tail rotor, to provide a platform for maintenance personnel working on the tail rotor's gear box. This is *not* the stabilizer's preferred location from a purely aerodynamic point of view. When confronted with the need to optimize RAM, engineers compromised with a system that worked well and also satisfied RAM needs. Given that the UH-61A's engine cowlings opened to become work platforms, nearly all maintenance could be done without the aid of workstands.

---

[14]K. I. Grina, "Helicopter Development at Boeing Vertol Company," *Aeronautical Journal*, September 1975, pp. 405-408; and "Vertol to Exploit New Rotor Technology," *Aviation Week & Space Technology*, January 24, 1977, pp. 46-47.

[15]Grina, "Helicopter Development," p. 406.

[16]Ibid., p. 407.

Vertol also chose to use fiber composite for the cabin floor. The floor's durability left Army evaluators impressed enough to insist that Sikorsky replace the titanium floor of its winning prototype with one of a composite material.

In at least one case, a minor design innovation proved to have unforeseen uses. Vertol's engineers designed landing gear that could be lowered to a "kneeling" position with the flip of a switch on the aircraft's exterior. Thus lowered, the aircraft could more easily be loaded aboard C-141 or C-130 transport aircraft. When they finally fielded the prototype, these engineers discovered that by lowering just one of the rear landing gears the tire of the gear opposite lifted off the ground, facilitating its removal. And this in turn lowered the amount of extra equipment needed to maintain the aircraft.

Boeing Vertol's prototype first flew late in November of 1974, just a month after Sikorsky first flew its UH-60A and 27 months after the UTTAS contract had been signed.

THE UTTAS TEST AND EVALUATION PROGRAM

Contractor flight testing of the UTTAS prototypes began in October 1974 and ended with source selection in December 1976. UTTAS flight tests totaled 2900 hours (contractor and government testing) on six flying prototypes; ground test vehicles logged a total of 2750 hours. Although these figures fall short of the 11,360 total test hours the service had projected for the originally scheduled 14 prototypes,[17] they nonetheless represent "more [test] hours than any other aircraft the Army has developed at the same point in its development."[18]

Before the service received the UTTAS prototypes for government competitive testing, each contractor logged several hundred hours of flight and ground tests on its own. Total ground test hours for the Sikorsky prototype, for example, amounted to 1214, of which over half were logged before government tests began. The Sikorsky prototypes also flew a total of 622 hours during this phase of testing. Boeing Vertol apparently logged even more hours on its prototypes during this period. Although the PMO approved the substance of all test plans during contractor testing, PMO personnel were less interested in RAM and other performance data during these tests than they would be during GCT. Contractor testing was thus a time for the firms themselves to surface problems in their aircraft.

From its ground tests, for example, Sikorsky learned the inadvisability of using grease rather than oil in the UH-60A's lubrication system. Normally, if a gear cracks or chips, metal chips fall to the bottom of the gearbox where they are detected by a magnetic chip detector. Early in the ground test phase, however, it became apparent that these chips usually stuck in the grease. Hence, cracks were not detected until the gear itself failed. The firm tried a number of alternative crack and chip detectors with little success. After one near-catastrophic accident with its ground test vehicle, Sikorsky returned—in less than one week's time—to an oil lubrication system.

Prototypes of both firms crashed during contractor flight tests. During an autorotation flare maneuver, Sikorsky's #3 prototype hit a wind shear that drove it, tail first, into the landing strip at 42 fps. Since the crash was caused by wind condition rather than technical

---

[17]See U.S. Senate, Committee on Armed Services, *FY 1973 Authorization for Military Procurement*, Hearings, 92d Cong., 2d Sess., Part 4, p. 2217.

[18]U.S. House, Committee on Appropriations, *DoD Appropriations for FY 1977*, Hearings, 94th Cong., 2d Sess., Part 5, p. 835.

problems, it fostered no changes in the UH-60A's basic design. Only the prototype's tail wheel was damaged. Vertol's #1 prototype emerged considerably more damaged from a crash on 19 November 1975, brought on when its tail rotor drive shaft failed, forcing it down in a forest near the company's test site on Long Island. Engineers determined that the shaft had been about 123 percent over its maximum rated rpm at the time it failed and that it had begun to resonate and bow outward until it hit the shaft cover and shattered. As a result, designers changed the length of shaft sections to alter its resonant frequency.[19] Both crashes were seen less as signs of major technical problems than as evidence that the UTTAS candidates were highly survivable aircraft.

Government competitive testing began in March of 1976 and involved a coordinated effort from three test agencies. Basic airworthiness tests were the province of the Army Engineering and Flight Test Activity, located at the Aviation School, Fort Rucker, Alabama. AEFA is the Aviation Command's own test agency. Development tests to ensure that prototypes met performance goals, MilSpecs, and the like were conducted by the Army's overall development test agency, the Test and Evaluation Command, part of the overall DARCOM framework (of which AVSCOM is also a part). The Army user's representative to the tests, finally, was the Operational Test and Evaluation Agency, which reported directly to the Deputy Chief of Staff for Operations, the user's central representative on the Army Staff. User, developer, and, within the developer community, the Aviation Command itself all had a hand in testing the UTTAS prototypes.

In the wake of congressionally dictated cuts in the number of UTTAS prototypes, the PMO had, as described earlier, restructured test schedules in an effort to maximize the number of tests relevant to RAM performance. As the time for GCT approached, the PMO also took pains to obtain agreement among representatives from all three agencies on precisely what RAM data were worth collecting. Here the service faced the problem that RAM data had never been standardized. Hence the UTTAS PMO had to invent a standard RAM collection format on which all test agencies could agree. This was accomplished before GCT began; from the moment GCT got under way, each prototype was accompanied by four PMO or AVSCOM engineers equipped with a standard form listing all relevant RAM criteria and requiring that all faults be logged. PMO personnel claim that this form has since become the Army's standard RAM data collection form.

Government testing ran each firm's prototypes through the following test schedule:[20]

1. Phase I, March 29-June 10, 1976: Development tests conducted at Fort Rucker, Alabama. 305 hours logged on each firm's prototypes.
2. Phase II, June 24-September 9, 1976: Operational tests at Fort Campbell, Kentucky. Also included the U.S. Navy's LAMPS evaluation. 258 hours on each firm's prototypes.
3. Phase III, October 10-November 3, 1976: Cold weather tests at Fort Wainwright, Alaska (emphasis on de-icing). 14.7 hours on one of each firm's prototypes.
4. Phase IV, October 10-December 8, 1976: Climatic tests ($-65°$ to $+125°$ F) in climatic hangar at Eglin AFB. 42 hours on each firm's prototypes.
5. Concurrent with Phases I and II, one prototype from each firm underwent engineering tests at Edwards AFB from April 5 through September 28, involving 158 hours on each prototype.

[19]See "UTTAS Crash," *Aviation Week & Space Technology*, November 24, 1975, p. 21; and "Boeing UTTAS to Fly After Repairs," *Aviation Week & Space Technology*, December 15, 1975, p. 43.

[20]See Warren C. Wetmore, "UH-60 Termed Low Technical Risk," *Aviation Week & Space Technology*, April 4, 1977, pp. 60-61.

For the Sikorsky entry, flight testing produced the following breakdown of flight hours:

622 — contractor flight hours
44 — preliminary Army airworthiness (AEFA tests)
476 — TECOM's developmental tests
255 — OTEA's operational tests
1397 — total flight test hours, Sikorsky prototype

In general, competitive testing demonstrated that each firm's prototypes just met most of the UTTAS RFP's performance requirements. The Sikorsky prototype attained a speed of 147 kn, for example, barely over the floor of the RFP's 145-175 kn speed requirement. Both prototypes surpassed the MTBF requirement of 2.6 hours, but only in the last 200 hours of testing. Each met endurance and payload requirements. Both prototypes just missed the floor of the RFP's rate of climb requirement, though testing suggested that this could be met during the program's maturity phase. And both were slightly over the contractually agreed-upon weight limits, as shown in Table C.3.

Table C.3

WEIGHT OF UTTAS PROTOTYPES

Contractor	Promised	Actual (during flyoff)	Estimated Production Configuration
Boeing Vertol			
Empty	9,601	10,490	9,784
Gross mission wt	15,024	15,929	15,195
Sikorsky			
Empty	10,460	10,853	10,366
Gross mission wt	15,850	16,387	15,879

SOURCE: U.S. House, Committee on Appropriations, DoD Appropriations FY 1977, Hearings, 94th Cong., 2d Sess., Part 5, p. 839.

Government tests surfaced a variety of minor technical problems in each firm's prototypes. The innovative fluidic stability augmentation system that Sikorsky's designers chose because it promised high reliability never lived up to that promise. The viscosity of the system's fluid changed with varying weather conditions and so did its performance. To compensate for this phenomenon, engineers added heating and cooling systems to the device to maintain near-constant fluid temperatures. But this only made the SAS more complex and less reliable. Since Sikorsky's designers had first chosen the fluidic system, the electronic microcircuitry revolution had permitted substantial improvements in the performance and reliability of the electronic SAS. By the time source selection was made, the UH-60A had been refitted with an electronic system.

Tests also surfaced problems with the Sikorsky prototype's stabilator (the helicopter's equivalent of a fixed-wing aircraft's horizontal stabilizer) located on the UH-60A's tail just below the tail rotor. As pilots "pulled pitch" just before landing, the main rotor's "propwash" pushed down on the stabilator's surface, forcing the aircraft's tail down and causing pilots to perform high-risk maneuvers to avoid damaging the tail. In response to this problem, engineers installed a one-piece stabilator that rotated on a cylindrical axle running through the aircraft's tail. During the approach to landing, the pilot could move the stabilator into a vertical position, eliminating the effects of downward propwash.

A Sikorsky prototype crashed during operational night maneuvers at Fort Campbell, Kentucky, revealing a quality control problem in production. Laminations on one of the aircraft's rotor blades debonded during flight, sending severe vibrations through the aircraft and forcing the pilot to crash land with a full infantry squad on board. Although the prototype landed in a pine forest, no one was hurt and the aircraft's transmission and rotor hub, as well as the debonded rotor's titanium spar, were undamaged. To cure the debonding problem, Sikorsky "went to a hot-cured lap joint of the glass fiber" laminations.[21] The crash was seen less as a major mishap than as proof that the Army's UTTAS candidate was indeed a highly survivable aircraft.

A minor problem with both the Sikorsky and Vertol prototypes developed during mountain testing near Edwards AFB, California. Crew members found that they had insufficient downward vision through each prototype's chin bubble to perform the flare manuever necessary to land at high altitudes. Both contractors reshaped their prototype's instrument panel to allow greater visibility. PMO personnel proffer this example as an illustration of the difference between user and developer tests; although both types of testing push the aircraft to the limits of its performance envelope, only user pilots do this under operational conditions and thus find many problems that developer tests do not detect.

Flight testing also proved the unreliability of the "lag-dampers" Vertol engineers had installed on their prototype's rotor hub. Attached to the base of each rotor blade, these devices dampen out vibrations associated with chordwise motion of the blade (lag). Because they knew lag-dampers to be notoriously unreliable, and because they felt that their prototype's semi-rigid rotor system would eliminate problems with this sort of vibration, Vertol designers originally proposed leaving lag-dampers out of their design entirely. The PMO took a very conservative line on this matter, however, and forced the inclusion of lag-dampers in the original prototypes. Flight tests showed that the devices were indeed unreliable and unnecessary, and they were finally removed.

As critical as some of these problems may seem, they fell a distant second in importance to the major problem revealed in both prototypes during government testing, excessive vibration. The UTTAS RFP specified a vibration requirement of 0.05 g, well below the Huey's average of 0.25 gs. During the bulk of competitive testing, however, both firms' prototypes averaged about 0.2 g vibration, moving the project manager to admit that on this requirement the UTTAS RFP was "too stringent for the state of the art."[22] Thus, the PMO finally relaxed the vibration requirement to 0.1 g.[23]

For Sikorsky, excessive vibration resulted largely from the short distance between the top of the airframe and the whirling rotor blade. To enhance transportability aboard cargo

[21]Wetmore, "UH-60 Termed Low Technical Risk," p. 61.
[22]Quoted in Wetmore, "UH-60 Termed Low Technical Risk," p. 61.
[23]"Vibration Prompted Army Risk Analysis," *Aviation Week & Space Technology*, April 4, 1977, p. 61.

aircraft, designers at Sikorsky had shortened the rotor shaft of their prototypes as much as possible. However, this brought the rotor down into turbulent air blowing up from the aircraft's windshield during flight. Hence Sikorsky's engineers lengthened their prototype's rotor shaft about 17 inches to move the rotor into free air. This "fix" also moved the prototype's vibration levels into the 0.03 to 0.1 g range.

Like their contemporaries at Sikorsky, Boeing Vertol designers kept the UH-61A's rotor shaft as short as possible, again to enhance transportability. Hence, the Vertol prototype also suffered from vibrations caused by the interference of turbulent air in the rotor's travel. But shaft length accounted for only part of the Vertol prototype's vibration problems. A more important source was the prototype's lack of an effective rotor isolation system to confine vibrations to the rotor blade. The pendulum type of absorber originally placed on the UH-61A's hub failed to do its job; the aircraft's semi-rigid rotor effectively transmitted vibrations in the rotor through the hub to the aircraft itself.

To solve this problem, Vertol engineers initially tried installing elastomeric springs in the rotor hub. Finding that these were of no value, they finally settled on metal springs. This experimental work took place, however, during the final months of GCT, and the attempt to use elastomeric springs cost the firm a month's time. Vertol flew its prototype with the metal spring isolation system a month after the competition had ended. That the UH-61A at that point achieved vibration levels of .05 g did the firm no good.

In announcing the UTTAS contract award to Sikorsky, the Assistant Secretary of the Army referred primarily to the UH-60A's advanced maturity and readiness for production. Vertol's Charles Ellis believed that this reference drew primarily from his firm's problems in solving its prototype's vibration level. "We didn't have the technology well in hand at the outset," Ellis told reporters. "The rotor isolation system represented new hardware, and the Army had to worry about whether we could do it for the weight we promised."[24] Because keeping risks low had been a major Army goal throughout the UTTAS program, it appears the Army emphasized that feature in its source-selection decision. That interpretation is strengthened by the fact that the Vertol prototypes outperformed the Sikorsky prototypes in the RAM category during GCT, as Table C.4 illustrates. Each firm's prototypes finally met the service's basic RAM requirement. With the RAM threshold crossed, risk assessment apparently became the major determinant in the source selection. And the problems Vertol encountered in designing a new rotor isolation system only emphasized the fact that Vertol's had been a higher risk project from the start.

Looking back on the tests, the UTTAS project manager mentioned two central features of the UTTAS test and evaluation. On the one hand, "side-by-side testing motivated the contractors to find the minor bugs and fix them." On the other hand, he argued that, because production had yet to begin, and because so many "tactical/operational shortcomings" had been spotted and remedied during the tests, the Army would need to make "fewer changes to the aircraft once it . . . [was] fielded."[25] The test results also illustrate that despite the most careful design program, many problems will almost certainly be revealed in the test program.

COSTS AND SCHEDULE

This section outlines the UTTAS program's actual costs and schedule for the development phase and projections (as of September 1980) for the procurement phase. They are

[24]"Vibration Prompted Army Risk Analysis," *Aviation Week & Space Technology*, April 4, 1977, p. 61.
[25]Wetmore, "UH-60 Termed Low Technical Risk," p. 61.

Table C.4

GOVERNMENT COMPETITIVE TEST RESULTS

Item	UTTAS Interim Goals	Development and Operational	Last 200 Hours
Boeing [a]			
MTBF	2.6	2.82	3.59
Mission reliability	.90 [b]	.963	.967
Fault corrective maintenance manhours per flight hour	4.3	.643	.466
Operational availability [d]	(c)	.849	.855
Sikorsky [a]			
MTBF	2.6	2.65	2.97
Mission reliability	.90	.952	.967
Fault corrective maintenance manhours per flight hour	4.3	.646	.632
Operational availability [d]	(c)	.853	.849

SOURCE: "Status of the Utility Tactical Transport Aircraft System Program," GAO Report to the Congress, February 25, 1977, Appendix I, p. 12.

[a] Figures include assumed failure rates for government-furnished equipment.

[b] Figure represents minimum acceptable values to be demonstrated during government competitive testing. No interim goal was established for this parameter.

[c] No interim goal was established for this parameter.

[d] Operational availability test results were computed using a 10 percent factor for aircraft not operational because of supply parts.

compared with the original estimates and the differences explained. An overview of the UTTAS program schedule from the release of the RFP to the transition from development to procurement is shown in Fig. C.1. However, a comparison of the program's *actual* and *baseline* schedule milestones provides a more useful point of departure for this discussion. As Table C.5 makes clear, the development phase of the UTTAS program began and ended roughly on schedule. However, the congruence between real and predicted milestones at either end of the program masks a certain amount of schedule distortion midway through the development phase: The program's schedule stretched out as development progressed but

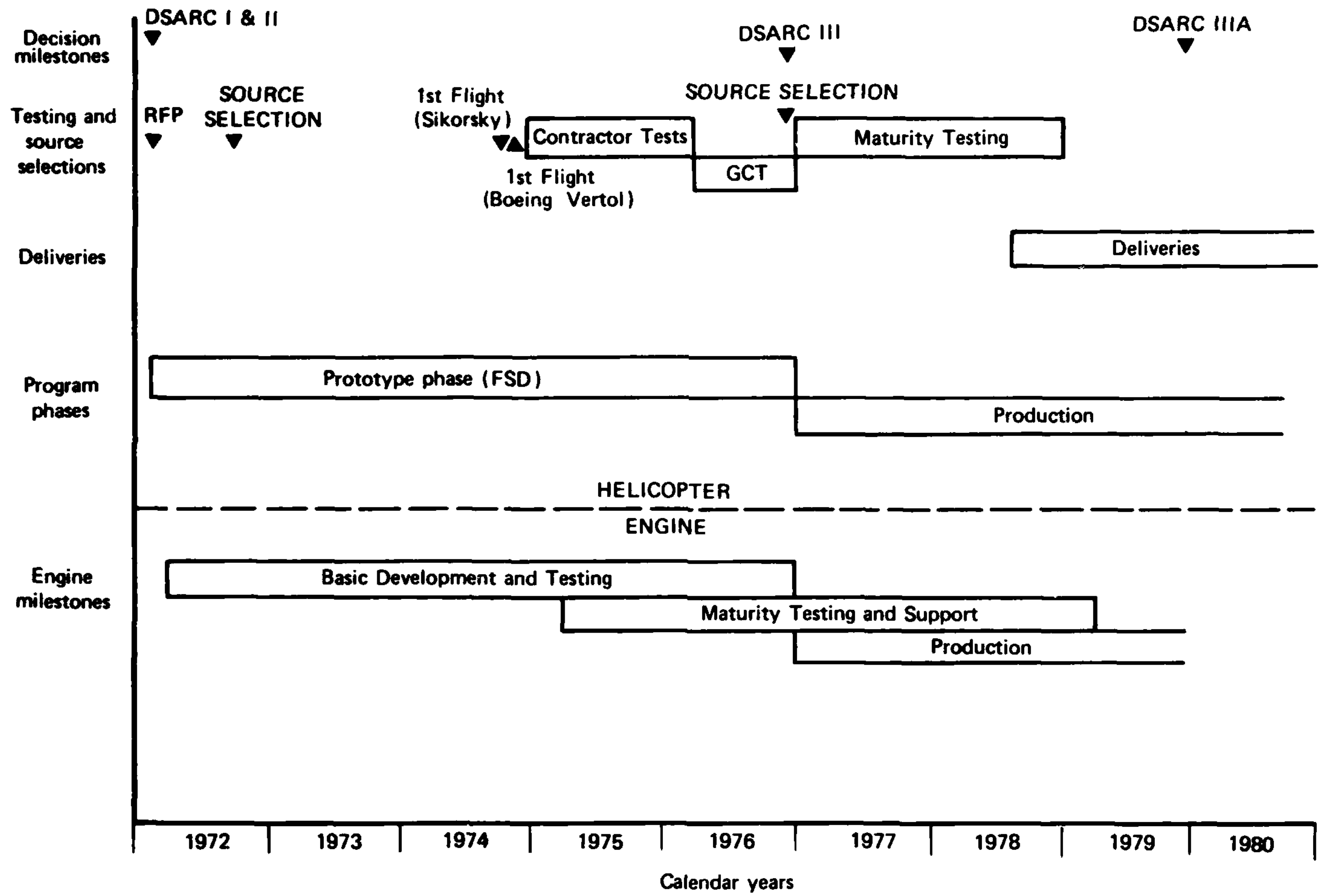


Fig. C.1—Overview of UTTAS program milestones

Table C.5

PREDICTED AND ACTUAL UTTAS PROGRAM MILESTONES

Event	Predicted	Actual
Engine contract	12/71	3/72
Airframe RFP	1/72	1/72
Airframe contract	9/72	8/72
First flight	9/74	11/74
Flyoff begins	9/75	3/76
Flyoff ends	9/76	12/76
DSARC III	9/76	11/76
First production aircraft accepted	8/78	10/78
IOC	6/79	11/79

SOURCE: UTTAS SAR, June 1980.

recovered sharply as source selection and production approached. Similarly, the production rate planned for the first three years of the procurement phase was increased shortly after DSARC III, only to be cut back a year later because of a funding squeeze.

Table C.6 presents the expected cost growth of the total UTTAS acquisition program as projected in the September 1980 SAR. The cost figures are shown in program base year (FY 71) dollars, then year dollars, and FY 81 dollars. In each case, separate cost variance distributions are shown for FSD and procurement as well as for the total overall program. The baseline DE is shown for each group, followed by the various cost changes according to several descriptive cost variance categories. The sum of the DE and total variance equals the CE as projected in September of 1980. To be consistent with the other prototype cases examined in this report, *the cost references in the following discussion will be in terms of FY 81 constant dollars except where otherwise stated.*

Unlike the other prototype examples in our study, the UTTAS competitive prototype effort did not precede the establishment of the DE cost predictions. Instead, it began at DSARC II and a parallel development continued until DSARC III. Thus, the UTTAS cost baseline did not benefit from any knowledge gained from the prototype phase of the program. However, this arrangement provided the Army with the opportunity of deciding which of the two contending models seemed most likely to yield the prescribed level of performance for the lowest unit cost, based on pre-production hardware. Since for large programs such as UTTAS the procurement phase has the greatest effect on the ultimate cost of the program, a wrong choice of design can have dire financial consequences. It is conjectural to estimate what the total cost of the UH-61 design would have been for the 1107 production helicopters had that model been selected at the outset and without competitive prototyping. However, the UH-61

Table C.6

UH-60 Program Acquisition Cost

($ millions)

Item	Base-Yr (FY 71) $ Cost	Base-Yr (FY 71) $ % of DE	FY 81 $ Cost	FY 81 $ % of DE	Then-Year $ Cost	Then-Year $ % of DE
Development (Quantities: DE= 16, CE = 10)						
Development estimate	357.3	100.0	738.2	100.0	409.9	100.0
Variance:						
Quantity	-20.2	-5.7	-41.7	-5.7	-22.0	-5.4
Schedule	1.4	.4	2.9	.4	3.0	.7
Engineering	.0	.0	.0	.0	.1	.0
Estimating	9.6	2.7	19.8	2.7	11.6	2.8
Other	12.6	3.5	26.0	3.5	18.5	4.5
Support	6.2	1.7	12.8	1.7	8.2	2.0
Economic					52.3	12.8
Total variance	9.6	2.7	19.8	2.7	71.7	17.5
Current estimate	366.9	102.7	758.1	102.7	481.6	117.5
Procurement (Quantities: DE= 1107, CE= 1107)						
Development estimate	1584.4	100.0	3378.3	100.0	1897.4	100.0
Variance:						
Quantity	.0	.0	.0	.0	.0	.0
Schedule	-80.3	-5.1	-171.2	-5.1	380.3	20.0
Engineering	-24.9	-1.6	-53.1	-1.6	-24.9	-1.3
Estimating	307.1	19.4	654.8	19.4	1341.1	70.7
Other	.8	.1	1.7	.1	1.4	.1
Support	-72.9	-4.6	-155.4	-4.6	132.1	7.0
Economic					1778.2	93.7
Total variance	129.8	8.2	276.8	8.2	3608.2	190.2
Current estimate	1714.2	108.2	3655.0	108.2	5505.6	290.2
Total program (Quantities: DE= 1123, CE = 1117)						
Development estimate	1941.7	100.0	4116.5	100.0	2307.3	100.0
Variance:						
Quantity	-20.2	-1.0	-41.7	-1.0	-22.0	-1.0
Schedule	-78.9	-4.1	-168.3	-4.1	383.3	16.6
Engineering	-24.9	-1.3	-53.1	-1.3	-24.8	-1.1
Estimating	316.7	16.3	674.6	16.4	1352.7	58.6
Other	13.4	.7	27.7	.7	19.9	.9
Support	-66.7	-3.4	-142.6	-3.5	140.3	6.1
Economic					1830.5	79.3
Total variance	139.4	7.2	296.6	7.2	3679.9	159.5
Current estimate	2081.1	107.2	4413.1	107.2	5987.2	259.5

SOURCE: September 1980 SAR.

prototypes cost more to fabricate than did the UH-60 prototypes, and this discovery provided a very useful input to the source-selection process. If carrying the competitive prototype program up to DSARC III revealed that the UH-60 could accomplish the mission satisfactorily at less cost, then the money spent on its development and on the evaluation of the competitive flyoff seems well justified.

The UTTAS program exceeded its development cost goals by 2.7 percent. Although this is far less than most other mature military acquisition programs, the UTTAS program manager was given a substantial assist by the Congress at the very beginning of the development phase when it directed the Army to reduce the number of test vehicles from six flying prototypes per contractor to three. As indicated in Table C.6, this gave the program a substantial pad to offset any future cost growth during development. However, even if we adjust the cost growth to compensate for the quantity change, the overall cost growth in terms of the original quantity is only 8 percent, a very commendable showing.[26] The amount of cost growth thus far in the procurement phase of the UTTAS program must be considered remarkable by any standard. A mere 8 percent cost growth for a ten-year-old program of this complexity is an unparalleled accomplishment. For the program as a whole, the total expected cost growth (as of September 1980) is 7 percent, or 8 percent if we adjust for the quantity variance.

A distribution of the UTTAS program costs, by acquisition phase, is shown in Table C.7. The UTTAS competitive prototype phase accounted for about 15 percent of total program costs as measured in constant dollars. Since one of the two designs would have had to be developed in the absence of competition, the cost of the extra design plus the flyoff is equal to about 8 percent of the total. This is considerably higher than the A-10 and F-16 programs and is explained in large part by the requirement for operational fidelity in the UTTAS prototypes, for the reasons cited earlier. Another partial explanation is the Army's CPIF contract, which allowed for the reimbursement of contractor overruns.

Table C.7

UTTAS TOTAL PROGRAM COSTS AS ESTIMATED, SEPTEMBER 1980
($ millions)

	Base-Year $ (FY 71)		Present-Year $ (FY 81)		Then-Year $ (FY 68-91)	
Item	$	%	$	%	$	%
Prototype	325.0	15.6	671.5	15.2	423.2	7.1
Other development[a]	41.9	2.0	86.6	2.0	58.4	1.0
Procurement	1714.4	82.4	3655.4	82.8	5505.9	91.9
Total	2081.3	100.0	4413.5	100.0	5987.5	100.0

SOURCES: Prototype cost: RDTE funding for FY 71 through FY 77 provided by UTTAS PMO; Total development and procurement: UH-60 SAR, September 1980.

[a]Including a small sum spent before FY 71.

[26]Actually a bit less than 8 percent because a part of the cost growth would not have occurred if the baseline number of R&D helicopters had been available for the tests.

The best way to come to grips with cost and schedule in the UTTAS prototype phase is to examine the program as it evolved chronologically. We do so below in two sections. The first examines the program's development phase, now complete. We thus can compare program predictions with program realities. The second section will examine the program's production phase as it has evolved.

The UTTAS Development Phase

In August of 1972 the Army let CPIF contracts to the following firms:

	Contract Target Price ($millions)	
Contractor	Then year $	FY 81 $
Sikorsky	$61.9	103.7
Boeing Vertol	$91.3	153.0

In part, Sikorsky's lower bid stemmed from the simpler design it envisioned. More important, Sikorsky had more experience than Boeing Vertol in building helicopters with the size and function the Army wanted in its UTTAS. The firm thus was able to use several parts from other helicopters, for example. And it had in stock test equipment that Vertol had to buy specifically for its UTTAS effort. Because of its greater experience, Sikorsky deleted from its company test plans some of the basic tests Boeing Vertol felt it necessary to perform. Finally, Sikorsky apparently had been more deeply involved than Vertol in the earlier contract work that had helped the service define its UTTAS needs; the firm thus entered the competition with more physical plant and intellectual capital than its competitor.[27]

We noted earlier that the Army pared the UTTAS development schedule to a length uncomfortably short in the view of both contractors. The service apparently took the same approach to contract negotiations. Vertol's initial bid amounted to about $120 million, but Army negotiators pared this down to its final value of $91.3 million, largely by cutting out much of the contingency funding the firm had allocated for the resolution of technical problems during the development. Both firms began work on their prototypes on budgets and within schedules that allowed very little margin for error or unexpected technical problems.

The first budget and schedule shifts were not long in coming; in 1973 the Congress directed that the service cut the number of flying prototypes in the program's development phase from 12 to 6 and reduced UTTAS funding accordingly. But this budget cut was out of phase with the spending plan, and the congressional action actually forced a two-month stretch in the program's flight schedule. Brigadier General Leo Turner, the project manager, told Senator McIntyre in 1973,[28]

> The money that you save in reducing the numbers of prototypes is in hardware. It is not in the initial design of the aircraft system, or in the initial component tests, or in wind tunnel tests

[27]For contract values, see U.S. Senate, Committee on Armed Services, *FY 1975 Authorization for Military Procurement*, Hearings, 93d Cong., 2d Sess., Part 5, p. 2630. For a discussion of the disparity between contracts given the two firms, see U.S. Congress, House Committee on Armed Services, *DoD Appropriations for 1975*, Hearings, 93d Cong., 2d Sess., Part 4, p. 1164.

[28]U.S. Senate, Committee on Armed Services, *FY 1974 Authorization for Military Procurement*, Hearings, 93d Cong., 1st Sess., Part 4, p. 2037.

> that the contractors have to do in the first year that they are working on the contract. As a result of the $13.6 million [then-year $] reduction, we did not have available money to place on contracts in the quantity that the contractors wanted, so we decremented those amounts with them and negotiated another first flight date, which is November 1974. That is still within the DCP threshold of the program.

Although the first flight date slipped two months and there were fewer test vehicles, the PM apparently was able to accomplish the program's essential test and evaluation objectives on time and thus retain the originally targeted date for source selection. Nonetheless, the $41.7 million savings in prototype hardware (see Table C.6) overstates the net savings of this cut by about one third. The service moved some of its tests from the competitive test phase to the maturity test phase of the program, causing some rescheduling expense; and competitive testing, now somewhat more crowded than the service originally had planned, rose in estimated cost by $12.8 million. This is shown in the Support category of Table C.6. Thus the net cost savings generated by the congressional action came to about $28 million.[29]

Contract work at Sikorsky and Boeing Vertol proceeded smoothly through 1973, when both firms began to encounter the kind of technical problems not uncommon to weapons development programs. Sikorsky fell behind schedule early in 1974 as it fabricated static and ground test vehicles. The reason: "changes made during the critical design and mockup reviews," coupled with "late delivery of major vendor items."[30] The company was soon back on schedule, however, and managed to fly its first prototype in October of that year, a month ahead of the (rescheduled) target date.

Boeing Vertol first encountered problems late in July of 1974, when fatigue failure in its semi-rigid rotor system bushings caused separation from a whirl test tower shaft. Although this by itself neither delayed the program nor raised its costs appreciably, the next year saw Vertol experience the most expensive and time consuming of the three prototype crashes that marked the program's RDT&E phase. The firm's #1 prototype had crashed on November 19, 1975; it returned to flight status on February 19, 1976. Army personnel estimated the overall delay to be only six to eight weeks. Repairs to the prototype cost $2.5 million, and the cost of the crash to the program as a whole (including the cost of delay, compressed test schedules and so forth) came to some $5.2 million.

These remain only the most visible sources of UTTAS schedule slippage and cost overruns. Personnel at both firms assert that several other technical problems, each of which took time and money to solve, began to appear as hardware construction and testing progressed. From 1974 onward, they argue, both firms began to experience increasing cost overruns as a result of technical problems.

But technical problems were not the only forces at work raising costs. The extraordinarily high inflation rate of 1974-75 had not been included in original cost estimates or contract values, and this created a large share of the cost increases Boeing Vertol and Sikorsky experienced during the course of the UTTAS development.

Contractors experienced other problems not directly associated with their designs that had an effect on that program's costs. A strike at Boeing Vertol, for example, forced higher level, higher paid personnel to work on that firm's #2 prototype, driving the costs of that prototype higher than would otherwise have been the case.

---

[29]FY 81 dollars derived from figures taken from U.S. Senate, Committee on Armed Services, *FY 1973 Authorization for Military Procurement*, Hearings, 92d Cong., 2d Sess., Part 4, p. 2211, and *FY 1975 Authorization for Military Procurement*, Hearings, 93d Cong., 2d Sess., Part 5, p. 2620.

[30]"UTTAS," *DMS*, May 1976, p. 4.

Overhead costs allocated to Sikorsky's UTTAS candidate rose partly in response to declining business elsewhere in the firm. General Turner told members of the McIntyre subcommittee,[31]

> When the Army and Sikorsky signed this contract, we had to agree to a projection of the amount of additional business that Sikorsky would have over the period of time in relation to the overhead rates. We agreed upon that projection, which I believe was about 31 units per year. Last fall Sikorsky was still not up to [that level of other business].

The Army, in other words, was being asked to carry about $4.5 million more of the firm's overhead than it had bargained for in setting the development cost target. The service tried to "pressure" the firm, with some success: "We [meaning Sikorsky, with the Army's prodding] have generated some new business [for the firm],"[32] General Turner told a concerned Senator Goldwater. Still, it seems clear that Sikorsky's UTTAS costs did absorb some extra overhead charges.

Problems with subcontractors also forced Sikorsky's costs upward. When the firm calculated its UTTAS bid in 1972, for example, it based its estimate of metal tooling costs on figures then available. But 1972 was a slump year for the metal tooling industry, and by 1974, when Sikorsky turned to that industry for help in constructing its prototypes, the economy was in a surge and metal tooling was in high demand. The industry thus extracted top-dollar rates from Sikorsky, and this in turn contributed to the firm's cost overruns.

For all of the reasons outlined above, the UTTAS program overran projected costs by some $12.5 million by the end of 1974.[33] For a moment, the Army considered slipping the program's schedule, paying for what it could in FY 1974 and adding the amount of the overrun to the next year's budget. The Navy intervened, however; unwilling to delay its search for a LAMPS candidate by six months, the Navy insisted that both of the UTTAS prototypes be completed on schedule. In response, the Army elected to allow the contractors themselves to fund the program in an effort to keep it as close to the original schedule as possible.[34] It promised to reimburse contractors out of FY 1975 funds, and in fact did so.[35]

Costs did not stop mounting in 1974, however; hardware testing had only begun, and more technical problems surfaced over the next year. Hence contractors—especially Boeing Vertol, which had the riskier design and the most expensive crash—actually put up more than $12.5 million. In January of 1975 *Aviation Week & Space Technology* reported that Boeing Vertol and Sikorsky had already put up $16 million and $5 million, respectively, in company funds. In FY 81 dollars, this is equivalent to about $35 million. And a year later a GAO report put UTTAS overruns at $54 million (about $80 million in FY 81 dollars), prompting House staff member Peter Murphy to ask Army representatives if "the $54 million figure [is] incorrect or are you asking the contractors to absorb this?"[36]

In a very real sense the Army *did* ask contractors to absorb a small share of this cost overrun. By 1976 the service was beginning to take criticism from the Congress for its reim-

---

[31]U.S. Senate, Committee on Armed Services, *FY 1975 Authorization for Military Procurement*, Hearings, 93d Cong., 2d Sess., Part 5, p. 2631.

[32]Ibid.

[33]"Costs to Force Stretch in AAH, UTTAS," *Aviation Week & Space Technology*, September 2, 1974, p. 22.

[34]Clarence A. Robinson, Jr., "Navy Picks Army UTTAS for LAMPS Role," *Aviation Week & Space Technology*, January 6, 1975.

[35]See *Aviation Week & Space Technology*, January 6, 1975, p. 17. The Army budget request for FY 1975 included the contractor reimbursement. The Congress appropriated the full amount.

[36]U.S. Congress, House Committee on Appropriations, *DoD Appropriations for FY 1977*, Hearings, 94th Cong., 2d Sess., Part 5, p. 841.

bursement policy. This came from the McIntyre subcommittee, as illustrated by the following exchange, which occurred in March of 1976:[37]

> MR. FINE: (Hyman Fine, chief assistant to the Senate Armed Services Committee) Referring to the UTTAS program, why is it necessary to pay back $7.4 million to contractors for work performed in fiscal year 1975? Why shouldn't they absorb it as part of their assumed risk and possibly recover most or all of it through IR&D procedures?
>
> MR. MILLER: (Edward A. Miller, Assistant Secretary of the Army for R&D) In the first place, the work performed was on behalf of this contract. It is, of course, a universal contract. It is my understanding that to the extent this contract is funded we are obligated to pay the allowable costs of the contractor from the funds available, if the contract is cost reimbursing.

The original contract *was* cost reimbursing. Faced with mounting resistance from the Congress, however, the service effectively converted that contract to a fixed-price version. In March of 1976 an Army witness told members of the House Committee on Appropriations that:[38]

> the Army project manager had told contractors that they are to deliver the most competitive prototypes they can within the funds available; that no further funds will be provided. . . . The Army does not condone or in any way encourage the expenditure of company funds in performance of the contract.

By this time contractors had just turned their prototypes over to the Army for competitive testing. Both contractors claim that competitive pressures encouraged them to continue investing company funds in their UTTAS candidates, though neither specified precise amounts.

In the source selection that followed the competitive flyoff, Sikorsky's UH-60 emerged as the preferred choice and it entered the "maturity testing" phase. Beginning in December 1976 and running concurrently with initial production, this phase of the UTTAS program's research and development involved tests aimed at qualifying the aircraft and its components for full flight certification. As the project manager told members of the Senate Armed Services Committee in 1974,[39]

> By [maturity testing] I am talking about the electromagnetic surveys the high altitude surveys, and other various tests that must be accomplished prior to fully qualifying the aircraft.

Due to end in August of 1979, this phase of the program suffered a tragic setback on May 19, 1978, when one of the three original UH-60 prototypes being used for maturity testing crashed into a river near the Sikorsky plant, killing all three crew members. The cause of this accident lay in a maintenance error:[40]

> Transducers designed to sense the air speed and automatically rotate the stabilator to the proper position were not reconnected following routine maintenance during the night before the crash.

[37]U.S. Senate, Committee on Armed Services, *FY 1977 Authorization for Military Procurement*, Hearings, 94th Cong., 2d Sess., pp. 3205-3206. Fine also had been instrumental in pushing through the original budget cuts that limited the UTTAS program to six flying prototypes.

[38]U.S. Congress, House Committee on Appropriations, *DoD Appropriations for FY 1977*, Hearings, 94th Cong., 2d Sess., Part 5, p. 841.

[39]U.S. Senate, Committee on Armed Services, *FY 1975 Authorization for Military Procurement*, Hearings, 93d Cong., 2d Sess., Part 5, p. 2623.

[40]See "Crash Cause," *Aviation Week & Space Technology*, July 31, 1978, p. 19.

Although the accident signified no major problem in the aircraft's design, it nonetheless forced a seven-month extension in the maturity test phase of the program and added almost $3 million in Schedule variance to the total UTTAS development cost.[41]

Finally, not to be overlooked in this listing of cost growth drivers in the UTTAS development phase, is the usual overoptimism in the original baseline cost estimate. A low estimate for airframe development is singled out as a primary cause of the $19.8 million underestimate shown for this category. However, as was also true of the A-10 development, program costs rose because of policy changes that occurred after the baseline DE had been formulated. For example, the Producibility Engineering Planning and Component Improvement Program efforts, previously funded elsewhere, were added to the acquisition requirements without compensating adjustment of the baseline DE. This "cost growth" was included in the Estimating variance category by the UTTAS PMO as was some unspecified share of the cost of the increased maturity effort described above. Although some downward adjustment in the Estimating cost variance category could be justified—by deleting the cost increases that stemmed from the inclusion of activities not covered by the original baseline DE[42]—the effect on UTTAS total cost growth would be slight.

In summary, the UTTAS program completed its development phase with remarkably little schedule slippage and cost growth. To be consistent with the other programs we can estimate cost growth in terms of the original number of development aircraft, deleting the savings attributed to the cut in flying prototypes from 12 aircraft to six. This yields a cost growth percentage for the development phase of the program of 8 percent. However, the PMO identified some cost increases that were directly caused by having to conduct the development testing with fewer aircraft than the plan called for. If these cost increases are subtracted, the cost growth drops to between 6 and 7 percent.

Procurement Phase

The procurement phase of the UH-60 program also has shown low cost growth relative to other mature contemporary acquisition programs, despite some recent setbacks. Procurement costs have risen to a point only 8 percent above the baseline estimates. In fact, before December 1979, the program showed procurement savings of 15 percent below the baseline. This favorable experience was, at first, largely the result of schedule compression, a rare phenomenon in the military acquisition area. Later, other programs chose the UH-60 helicopter for their particular applications, intermingling their equipment demands with those of the UH-60. Although this inevitably caused some delay in outfitting the operational squadrons, it added to the overall production quantity, and the learning curve provided additional cost benefits to this program. A brief summary of the cost and schedule experience during the procurement phase is shown below.

On December 23, 1976, the Army awarded Sikorsky an FPIF contract to produce 15 UH-60s. On the same date, it awarded GE an FPIF contract for production of 53 T700 engines. The Sikorsky contract included options for the purchase of up to 330 additional aircraft over the next three years, the length of the program's low-rate initial production phase.[43]

The initial production cost estimate for the program had been based on the production of

---

[41]UH-60 SAR, June 1979, p. 9; and Griffiths, "Army Grounds UH-60A," p. 15.

[42]Or, alternatively, by increasing the baseline estimate by the amount of the added costs.

[43]UH-60 SAR, June 1979, p. 3. On 14 October 1977 the Army exercised its first production option for 56 additional aircraft, and on 17 October 1978 it exercised the second for 129 aircraft.

85 aircraft over this phase of the program. Based on the perceived success of DT/OT II, however, the service chose to increase production at Sikorsky to a total of 200 aircraft, moving from 15 aircraft the first year to 56 in the second and 129 in the third. As service representatives put it to the McIntyre subcommittee in March 1977,[44]

> Based on the results of the Development and Operational testing ... it was determined by the Independent Operational Evaluator that there were no outstanding issues which would require OT III [a separate set of "maturity phase" tests pursuant to high-rate production]. Further, the UTTAS program was considered low risk based on the findings of the UTTAS Source Selection Evaluation Board.... In addition, the prototype had surpassed the interim RAM goals and the risks associated with achieving maturity RAM goals were low.

Members of the DSARC approved the production rate at the DSARC III meeting in December 1976. The move was expected to save the equivalent of about $142 million in FY 81 dollars for the program's production phase.[45]

Another major change in procurement phase cost estimates up to December 1979 resulted from accounting changes: Stock fund spare and repair parts were subtracted from the UH-60 current estimate and transferred to another part of the Army budget. In addition, the requirements for initial spare and repair parts were reduced. The two changes together pared $290 million from the procurement cost estimate.[46]

The deletion of some radio equipment and instrumentation saved about $53 million, and at that time there was a $32 million overestimate acknowledged in the baseline DE. Together these savings added up to the equivalent of $517 million in FY 81 dollars, or a cost reduction of 15 percent for the procurement phase. Unfortunately, this situation began to erode at the start of FY 80.

From the program's start, the service had expected delivery of the first UH-60A in August 1978. The crash of a prototype set the delivery date back by two months, however, and the first production aircraft reached Fort Campbell and the 101st Airmobile Division in October 1978. As of July 1979, seven more production aircraft had arrived at Fort Campbell, where they were assigned to the 158th Battalion for a 600-hour program of force development testing and experimentation.

In July 1979 all 11 operational UH-60s (eight production models and three prototypes) were grounded indefinitely when a hydrogen embrittlement problem was discovered in one of the aircraft's primary servo mechanisms. In checking these items, which help control the aircraft's main rotor, Bertea Corporation of California, their manufacturer, found that the annealing process it had used to harden metal parts in the mechanism had not strengthened them as much as had been predicted. Bertea thus recalled the entire lot that had been shipped to Sikorsky, making it necessary to ground the fleet. The fleet was restored to flight status about six weeks later, but it was reported that "there is still uncertainty as to whether a new primary servo mechanism heat-treating process will degrade survivability" of the aircraft.[47] The grounding slipped the UH-60 production another two months, and in December the Army announced its decision to reduce the peak production rate from 145 per year to 96.

In part the Army's decision to decrease production rates came as a result of consider-

[44]U.S. Senate, Committee on Armed Services, *FY 1978 Authorization for Military Procurement*, Hearings, 95th Cong., 1st Sess., Part 5, p. 4007.
[45]UTTAS SAR, December 1976.
[46]UH-60 SAR, June 1979, p. 9.
[47]"Black Hawk Schedule Restoration," *Aviation Week & Space Technology*, September 10, 1979, p. 26.

ations lying outside the program. In 1979 the Army found itself facing a substantial increase in the cost of its weapons acquisition program as a whole. The total value of Army major SAR programs (in FY 81 dollars) rose from $28 billion in December 1976, when the UH-60 production phase began, to $41 billion by December 1979. That amounts to 46 percent real growth and it forced the service to reassess its priorities, a process begun during its FY 81 planning, programming, and budgeting cycle. The reassessment apparently ranked armored vehicles above aircraft in procurement priority, since the XM-1 production schedule remained nearly unchanged, while the UH-60 (as well as the AAH and several missiles) suffered a drop in production rate.[48]

In the UH-60 case, however, the decision to lower production goals apparently was not simply a matter of setting priorities among programs; the Army also "questioned the capability of the contractor to produce at the programmed level within the funded delivery periods."[49] The June 1980 SAR noted that Sikorsky was having "airframe production start-up problems." These problems appear to have made the cut in the production rate at least partly a recognition of program realities. In October 1978, for example, the Army contracted for 129 aircraft over the next fiscal year. However, shortly after the end of that fiscal year—in November 1979—the Army modified the contract option to reflect the procurement of 90 instead of 129 aircraft, indicating that Sikorsky simply was unable to meet the demands of the original production option.

In any event, the Army's decision to cut the peak production rate from 145 aircraft per year to 96 broke the four-year production contract it had negotiated with Sikorsky in 1976. As one Army witness before the Senate Appropriations Committee noted,

> By reducing quantities, the Army reopened contract options which were negotiated back in 1976. The impact was the full brunt of inflation, realized manhours and materials costs and reduced economics of production.[50]

This suggests that, to the extent that actual costs of producing the UH-60 had been increasing, Sikorsky had been absorbing these increases as part of meeting contract obligations negotiated in 1976. Obviously the company would have sought to recover these increases when the original contract expired, regardless of any change in production rate.[51] The increases appeared when they did because the Army decided to renegotiate the contract. In the December 1979 UH-60 SAR, procurement cost growth rose from −15 percent to +2 percent and this upward trend has continued. The figures in Table C.6 show that procurement cost growth as of September 1980 stood at 8 percent. The primary cause for the increase was identified as estimating errors. To be more specific, the blame is shared by the following items:

1. The contractor startup problems mentioned earlier and production inefficiencies. At the Army's request, Sikorsky "has initiated a major program to reduce production costs to include a reorganization of the production management team; daily inten-

---

[48]David R. Griffiths, "Army Fund Plan Provides for Modest Modernization," *Aviation Week & Space Technology*, January 19, 1981, p. 23; and "Army Aircraft Lose Priority to Tanks," *Aviation Week & Space Technology*, January 12, 1981, p. 18. According to the latter article, the XM-1 program was actually to receive more funding than originally planned, at the expense of Army aircraft and missile programs.

[49]U.S. Senate, Committee on Appropriations, *DoD Appropriations for FY 1981*, 96th Cong., 2d Sess., Part 5, p. 1248.

[50]Ibid.

[51]Sikorsky at that time would be in a good bargaining position as the sole-source supplier.

sive management reviews to correct deficiencies which are cost drivers on the production line, e.g., out-of-station work arounds."[52]

2. Use of an updated avionics cost estimate that presumably reflects higher than expected costs for these components.
3. Use of a flatter experience curve slope for the engine. The T700 engine was itself the product of a prototyping program that began in 1967. Against this, however, the Army itself began to purchase more performance than it had originally required from this engine as early as 1978. More recently, the Navy, which uses the UH-60 airframe/engine combination for its LAMPS program, has begun upgrading the engine still further. The Army is helping to defray the additional costs of this process and will use the improved engine in its UH-60s.[53] This suggests that the T700 may be "a moving target": the design keeps changing and as a result the effect of the learning curve is arrested.
4. Sikorsky's "excellent performance . . . in achieving contract performance incentives, associated with weight reduction . . . exacerbated the projected funding shortfalls"[54] for the program. In short, the firm has succeeded in winning incentive awards for weight reduction that were not in the original estimate, thereby increasing program costs. This cost growth is considered preferable to the reduced rate of climb that had resulted, during the prototype test phase, from excessive weight.
5. Revised cost estimating methodology, presumably to match the remainder of the higher realized costs.

Together these changes contributed 19 percentage points of the present UH-60 procurement cost growth. Although a few of the items seem out of place in the Estimating variance category, identifying the root causes of the sudden cost rise as low initial estimates seems a more rational interpretation than simply charging it all against the schedule change per se, which provided the opportunity to renegotiate contract terms.

The only other cost increase is the very minor amount shown in "other." This is the addition of funds needed to offset the first year airframe production cost overruns. All of the other cost variance categories register negative cost growth. However, Support variance before December 1979 represented an even greater savings than it does at present. The recent offsetting increase occurred in the costs of spare engines and spare parts as a consequence of similar increases in the costs of the prime equipment.

Adding SOTAS and QUICK FIX as UH-60 users resulted in savings to the parent program that outweighed the effect of the reduced production rate. That is, the aircraft for these new programs will consist of the earlier, more costly models, thereby pushing a portion of the UH-60 deliveries to a point further down the learning curve. These cost savings, plus the decision to eliminate certain radio equipment and instrumentation, helped to offset the estimating errors described above so that overall cost growth—despite a rather dramatic increase over a period of one year—is still among the lowest of the current collection of military acquisition programs.

With regard to the DTC goal, it is not possible to directly relate the current UH-60 flyaway cost to the approved goal. The original goal was $600,000 per aircraft, expressed in FY 72 dollars (not base-year dollars). That goal, again in FY 72 dollars, has been raised over

[52]U.S. Congress, House Committee on Appropriations, *DoD Appropriations for FY 1981*, 96th Cong., 2d Sess., Part 9, p. 54.

[53]Ibid., pp. 51-52.

[54]U.S. Senate, Committee on Appropriations, *DoD Appropriations for FY 1981*, 96th Cong., 2d Sess., Part 5, p. 1248.

the years to $951,000 and more recently to $1.016 million to account for nonrecurring investment and other cost elements that cannot easily be segregated from the flyaway cost figures. System project management, system test and evaluation, and warranty costs, commonly included in the DTC goals of other acquisition programs, are specifically excluded from the UH-60 goal. The revised goal covers 1107 airframes and 4700 engines and assumes a production rate of 14 airframes per month. The current flyaway cost estimate represents a lower production rate, with UH-60s interspersed with variants for other programs. Without more detailed cost data it is not possible for an outsider to estimate what the cost growth might be in terms of the specific assumptions that underlie the UH-60 approved goal. However, the flyaway DTC goal of $1.399 million (in FY 72 dollars) given in the June 1980 SAR is 38 percent above the approved goal of $1.016 million.

OBSERVATIONS

As the UH-60 program moves further into its production phase it will allow increasingly interesting judgments to be made about the use of competitive prototyping through full scale development as an acquisition strategy. Examining the production process at Sikorsky and the unit cost of the produced item as it has evolved so far, however, does not lend much credence to the expectation that prototypes enhance the accuracy of subsequent production cost estimates. The increase in the UH-60 cost projections noted in Table C.6 did not result from insights gained from the prototype phase; they occurred after production had been under way for three years. In fact, the program CE projected immediately following the prototype phase actually was lower that the original DE baseline. Compared with the program cost estimate made at the time of DSARC III, the cost growth estimate as of September 1980 would be 23 percent.

Charting the UH-60's RAM statistics as the aircraft accrues real field experience will permit future judgments as to the worth of the U.S. Army's extensive emphasis on RAM performance in the design of its prototypes. On the basis of the ongoing operational demonstration, the Army appears satisfied that the UH-60 will meet the RAM specifications.

What does the UTTAS program teach us now? Three points deserve mention here. First, insofar as prototyping made it possible to use competition in the project, it helped create powerful incentives for contractors to adhere to the service's requirement in a stressful environment. Despite the Army's view that the UTTAS was a low-risk program, neither contractor fully met the service's requirements for cost, schedule, and performance, suggesting that under the schedule the service imposed on the project those requirements were quite demanding. Moving faster than they would have done under normal conditions, and operating, finally, without service funding, both contractors pushed hard to meet those requirements. Competition for the large procurement contract seems to have been the major force behind these efforts.

The second point concerns the Army's approach to managing the project. Given the power of competition in the project, it is difficult to explain the Army's inflexible, heavy-handed control of both contractors. A more austere monitoring program should have led to a similar outcome. However, the Army's managerial approach did not greatly slow the project. Lack of austerity does not seem to have cost the service time, in other words, or for that matter the money that pays for the extra time. Tight management control by a program office may not have all the disadvantages often accorded it.

Finally, the UTTAS program suggests that emphasizing costs and RAM early in the

design of a new system may affect that design markedly. Contractor and Army personnel alike noted that design engineers often lose sight of these factors if left to themselves. Discussions with cost and RAM team members thus raise new issues for designers, with tangible results in terms of the designs they finally submit. Insofar as the prototyping effort preceded procurement, it left contractors free to incorporate needed changes without having to alter tooling or production hardware that ordinarily is produced concurrently. This allowed the service to take maximum advantage of these novel elements of the UTTAS design process.

Appendix D

THE ADVANCED ATTACK HELICOPTER PROTOTYPE PROGRAM[1]

The objective of the Advanced Attack Helicopter program, in the words of its first program manager, was "to develop and procure a fully integrated attack helicopter that meets the military need and produce it within a recurring unit-production cost objective of $1.6 million in constant fiscal year 1972 dollars."[2] By fully integrated he meant a helicopter designed and built to carry a specific set of weapons, rather than one designed for another purpose or to carry another set of weapons, but to which new weapons have been added. The service planned to purchase 472 Advanced Attack Helicopters, to be deployed primarily in the European theater for antitank missions in support of ground forces and under the control of ground force commanders.

The Army used prototypes in a two-phase approach to the aircraft's development. After publishing the AAH RFP in November 1972, the service awarded contracts to Bell Helicopters International and Hughes Helicopters to competitively develop basic airframe and engine combinations. These were tested in 1976, and the program's second phase commenced when Hughes received a contract to add weapon systems and fully develop the aircraft.

BACKGROUND TO THE AAH REQUIREMENT

Army aviators experimented with using armed helicopters to provide close air support throughout the 1950s. The helicopter seemed ideally suited to provide such services, because it operated in the "low-and-slow regimes of flight" and was exceptionally agile.

Within months after taking office as Secretary of Defense, Robert S. McNamara sought to expand upon and formalize this early experimental work by ordering the Army to take a "bold new look" at airmobility concepts "in an atmosphere divorced from traditional viewpoints and past policies." In response, the service formed a Tactical Mobility Requirements Board. Named as president of the Board was General Hamilton H. Howze, an aviator who had participated in many of the early armed helicopter experiments both as director of aviation for the Army Staff G-3 (Operations) and as commander of the 82d Airborne Division. The Board thus came to be known as the Howze Board. It met from April through August of 1962.[3]

The Howze Board's final report cited a wide range of applications for airmobility in support of the Army's ground combat mission. It called for the formation of airmobile divisions and air assault brigades in which aircraft, notably helicopters, would rapidly transport troops and supplies, as well as supporting fires around the battlefield. On the subject of aircraft armed for the fire-support role, the report concluded:

---

[1]Geraldine Walter assisted in the preparation of this case study.

[2]See the testimony of Brigadier General Samuel G. Cockerham, U.S. Senate, Committee on Armed Services, *FY 1976/197T DoD Authorizations for Military Procurement*, Hearings, 94th Cong., 1st Sess., Part 8, p. 4431.

[3]For a series of summary articles covering the Howze Board's genesis and activities, see General Hamilton H. Howze, "The Howze Board," Part I, *Army*, February 1974, pp. 8-14; Part II, "Airmobility Becomes More than a Theory," *Army*, March 1974, pp. 18-24; and Part II, "Winding Up a 'Great Show,'" *Army*, April 1974, pp. 18-24.

Army aircraft, fixed and rotary wing, armed with appropriate weapons, are capable of delivering a measure of fire support for conventional airmobile forces, of escorting helicopterborne forces, and executing close-in visual, photographic, radar, and IR reconnaissance.[4]

In 1963, largely as a response to the Howze Board's recommendations, the Army began development of its first heliborne fire support system, the Cheyenne. The service wanted the Cheyenne to be primarily an escort ship for "helicopterborne forces," as mentioned in the Board's conclusions. It thus sought a helicopter capable of leaving the convoy, engaging enemy aircraft or gun emplacements, and then returning to its convoy formation.

This mission scenario made the Cheyenne requirement a very demanding one. On the one hand, to leave and return to a convoy in the manner envisioned demanded fairly high speeds; the Army's stated speed requirement of over 200 kn represented an extremely high speed for rotary-wing aircraft. On the other hand, to coordinate and control fire from the Cheyenne's various weapon systems, the service wanted a sophisticated central computer on board the aircraft and a high degree of sight stabilization. The need for both speed and fire control pushed the Cheyenne requirement to fairly high levels of uncertainty and risk.

The Army published its RFP for the Cheyenne in August 1964, and in November of that year it selected Sikorsky and Lockheed-California to pursue contract definition. Largely because its proposal featured an innovative "rigid rotor" that promised greater speed and stability than Sikorsky's conventional rotor design, Lockheed won this design competition. In March 1966 the Army awarded the firm a fixed-price, incentive contract with a ceiling of about $89 million for the development of ten flying prototypes plus one static test vehicle. Lockheed was expected to deliver the first production vehicle in September 1968. The contract left the Army with production quantity options ranging upward from 375 aircraft. Although the precise unit cost of the finished Cheyenne depended upon the option chosen and the production rate, the Army projected the unit cost to be about $2 million.[5]

Technical problems soon produced cost growth and schedule slippage in the Cheyenne program. First warnings of such difficulties surfaced in 1968, when the Assistant Secretary of the Army for R&D announced that the aircraft was suffering from instability associated with its rigid rotor. In 1969 significant cost growth was reported, and in March of that year, only six months before the Army was due to receive its first production Cheyenne, one of the test vehicles crashed, killing Lockheed's test pilot. The service terminated Lockheed's production contract, and Lockheed began further development work on the aircraft. But by 1971, the project had absorbed a total of $265.2 million in R&D funds, the aircraft's unit cost was estimated to be nearly $2.6 million (FY 72 $), and the program was in trouble both in the Congress and in OSD.[6]

In response to the project's cost and scheduling problems, in January 1972 the service convened a special task force to survey the situation. Chaired by General Sidney Marks, the "Marks Board" was given two basic tasks. First, it was to reevaluate the requirement against which the Cheyenne had been developed, determining in the process the "minimum acceptable operational characteristics" for an attack helicopter. Thereafter, it was to test the Cheyenne and any other readily available attack helicopters against the new requirement.[7]

---

[4]Ibid.

[5]U.S. Congress, House Committee on Appropriations, Subcommittee on the DoD, *DoD Appropriations for FY 1972*, Hearings, 92d Cong., 1st Sess., Part 9, pp. 303-330, esp. pp. 305-306.

[6]Ibid., pp. 305, 313, 322. See also Brooke Nihart, "Cheyenne Dead After Lingering Illness," *Armed Forces Journal*, September 1972, p. 60.

[7]U.S. Congress, House Committee on Appropriations, Subcommittee on the DoD, *2d Supplemental Appropriations Bill for 1973*, Hearings, 93d Cong., 1st Sess., Part 3, p. 54.

By the time Marks and his associates first met, few in the service questioned the importance of maneuverability rather than speed in ensuring the attack helicopter's survival. At the same time, few were willing to take on a technically demanding, high-risk project like the Cheyenne development.[8] The Marks Board concluded the first of its two missions by noting that "the Cheyenne requirements for speed, automatic weapon accuracy, navigational precision, turreted weapons, and other sophistication were beyond the Army's barebones needs."[9] In the words of the Army's Chief of Aviation, "What resulted from the requirements review was a somewhat smaller, slower, more maneuverable and more survivable aircraft optimized for nap-of-the-earth flight and survivability in a high-threat environment."[10]

In April and May of 1972 the Marks Board ran tests comparing flying prototypes of three attack helicopters against its newly formulated requirement. Prime among these prototypes was the Cheyenne. But the Board also tested two company-sponsored prototypes whose development had been funded by the firms offering them. One of these was Bell's "King Cobra," a product improvement over that firm's Cobra design. The other was a prototype gunship that Sikorsky rather hastily put together (using its CH-3 as a basis for the design) called the S-67 "Blackhawk" (in no way related to the "Black Hawk" utility helicopter that Sikorsky is currently producing for the Army). Together, these three represented the sum total of available attack helicopters.

None of these three aircraft met the Marks Board's requirement. Aside from being "overdesigned" for the new requirement, the Cheyenne lacked agility and a proven rotor system.[11] Sikorsky's prototype evinced poor antitorque control at high altitudes and poor climb capability on hot days. And Bell's King Cobra stretched Bell's basic Cobra design to the limits; as a consequence, it lacked potential for further growth. In addition, its cockpit was cramped, it lacked night and foul weather instrumentation, and could carry limited ordnance loads. Finally, neither company-sponsored aircraft originally had been designed to carry the TOW antitank missile system, which was at the time the prime candidate for arming the Army's attack helicopters.[12] Thus, neither was a "fully integrated" system.

By the time the Marks Board had evaluated these three aircraft, the Army had further tested the attack helicopter concept. In the spring of 1972 TOW-equipped Cobra gunships engaged in mock combat against a German Army tank platoon and a Vulcan antiaircraft gun system deployed in Soviet tactical formations. These tests reinforced the importance of maneuverability—embodied in the use of "nap-of-the-earth" flight—in enhancing helicopter survival. These were the last major conceptual tests conducted before the AAH program began.

The Army Systems Acquisition Review Council recommended on August 7, 1972, that the Cheyenne program be terminated in favor of a new program. On August 10 service representatives approached the Congress with a budget request for $40 million—$3.5 million to end the Cheyenne program and $36.5 million to initiate a follow-on program. Meanwhile, the Army's Combat Development Command worked the Marks Board's idea for an attack helicopter and the European test results into a formal Military Need document. This docu-

---

[8]As the AAH program's first program manager put it in 1973, "one of the major lessons that we learned from the Cheyenne program was that we bit off an awful lot of R&D at the same time. . . . Our [AAH] program is designed now to go with knowns to reduce this technical risk as much as possible." U.S. Senate, Committee on Armed Services, *FY 1974 Authorization for Military Procurement*, Hearings, 93d Cong., 1st Sess., Part 7, p. 4791.

[9]Quoted in U.S. Congress, House Committee on Appropriations, Subcommittee on the DoD, *2d Supplemental Appropriations Bill for 1973*, Hearings, 93d Cong., 1st Sess., Part 3, p. 54.

[10]Ibid.

[11]See the Army Chief of Aviation's testimony, U.S. House Committee on Appropriations, Subcommittee on the DoD, *2d Supplemental Appropriations Bill for 1973*, Hearings, 93d Cong., 1st Sess., Part 3, p. 55.

[12]Ibid.

ment became the basis for the service's first AAH proposal, which it offered to the DSARC late in September 1972.

The design-to-cost goal of $2.0 million (FY 72 $) that the service included in this first AAH proposal proved too high for members of the DSARC, however.[13] These individuals were aware that the U.S. Air Force had just initiated its AX project, aimed at producing an aircraft whose mission was similar to that of the Army's AAH, but with a cost goal of only $1.4 million (FY 72 $). They saw no reason for spending more money on an attack helicopter than on the AX. Thus, they ordered the service to scrub its AAH requirement to bring its DTC goal down to a competitive $1.4 million.

It is not clear what changes the Army made in its AAH requirement between September and November 1972, when it offered its second AAH program proposal to the DSARC. Journal articles published at the time suggested that the service had met OSD's cost limit by promising increased commonality between the AAH and the utility helicopter (UTTAS) project it had initiated less than a year before.[14] The basic performance goals specified in the Army's original AAH requirement probably remained unchanged.

Although the second AAH program proposal met with some criticism from members of OSD/Systems Analysis, Deputy Secretary of Defense Kenneth L. Rush nonetheless approved the proposal on November 10, 1972.

THE AAH PROGRAM DESIGN

On November 15 the service released its AAH RFP to industry. That RFP asked for performance capabilities as shown in Table D.1.

Table D.1

AAH CHARACTERISTICS

Performance (primary mission)	
Hover out of ground effect	4,000 ft at 95° F
Airspeed-cruise	145 kn
Lateral acceleration	.25/.35 g to 35 kn
Endurance	1.9 hr
Ordnance (disposable)	1,300 lb
Equipments	
Passive IR protection	2.75 in FFAR
Gunners IR night vision	Loran navigation
30mm cannon	Fire control computer
TOW missile	Avionics
Laser rangefinder	Twin engines

SOURCE: U.S. Senate, Committee on Armed Services, FY 1974 Authorizations for Military Procurement, Hearings, 93d Cong., 1st Sess., Part 7, p. 4781.

[13]Brooke Nihart, "Army Gets Go-Ahead for Scrubbed Down AAH," *Armed Forces Journal*, December 1972, p. 14.
[14]Ibid.

The service regarded the project as a fairly low-risk enterprise. "Actually," Chief of Army Aviation William Maddox told members of the Senate Armed Services Committee, "we have scrubbed our requirement very carefully to get down to the minimum requirement which we feel we will need for the 1980s." He added elsewhere that the service expected "to be probing no new technical frontiers. Requirements generally have been relaxed from the previous [Cheyenne] development."[15]

The AAH RFP allowed contractors to choose any engine they felt would meet the Army's needs. However, only GE's T700 engine, then being developed for the UTTAS helicopter, was reasonably well developed and promised to yield the kind of performance necessary to meet the service's requirement. The T700 was in fact a major advance over previous helicopter engines, offering a power-to-weight ratio twice that of the engine in the Army's standard UH-1 utility helicopter. Both winning AAH contractors chose the T700.

Bidding contractors were asked to submit two separate proposals, each with its own structural implications for the program:

1. A sole-source development proposal that the service could select should one contractor's bid look clearly superior to all others.
2. A proposal for competitive development of the airframe/engine and 30-mm gun combination, to be followed by a sole-source second phase during which the major subsystems (the vehicle's antitank missile system) would be integrated into the airframe.

The service made it clear to industry from the start that only a most unusual case would lead it to choose the first alternative. In fact, a host of forces within the government made the first choice highly unlikely. Deputy Secretary of Defense David Packard favored the use of competition where possible, and OSD representatives to the first AAH DSARC had made it clear that the AAH program would do well to look like the ongoing AX project—a competitive effort. And the Army itself preferred competition for its positive influence on the control of costs. As the Army's Chief of Aviation pointed out to the Senate Armed Services Committee in 1973, "we feel that keeping the competition is going to give us a cheaper aircraft."[16] The second alternative thus became a natural choice.

The Army's concern for the project's cost led it to limit the competition in three ways. First, although five firms answered the AAH RFP, the Army made it clear that it would limit the development competition to two contractors. Second, cost considerations limited the duration of the program's competitive phase to airframe development only. To be sure, the service's experience with the Cheyenne, King Cobra, and Black Hawk suggested that building the basic airframe was the riskiest part of helicopter development; weapons and other subsystems could be added later with somewhat less risk. In the AAH case, however, cost considerations loomed more important; the costs of keeping two contractors going through the subsystem integration phase of the program threatened to "drive . . . development costs far too high."[17] "We feel that to take that approach," one Army witness told members of the Senate Armed Services Committee in 1973, "roughly one-half of the contract cost would be thrown away in the development of a subsystem for the loser."[18]

---

[15] U.S. Congress, House Committee on Appropriations, Subcommittee on the DoD, *2d Supplemental Appropriations Bill for 1973*, Hearings, 93d Cong., 1st Sess., Part 3, p. 78.

[16] U.S. Congress, House Committee on Appropriations, Subcommittee on the DoD, *2d Supplemental Appropriations Bill for 1973*, Hearings, 93d Cong., 1st Sess., Part 3, p. 56.

[17] Ibid.

[18] U.S. Senate, Committee on Armed Services, *FY 1976/197T Authorization for Military Procurement*, Hearings, 94th Cong., 1st Sess., Part 8, p. 4446.

Finally, cost considerations led the service to limit the number of prototypes competing contractors would build. As a service representative told the Senate in 1973:[19]

> We have restricted our initial phase of the development program to two flying prototypes only to check out what we feel are the most critical aspects, and that is the performance as it relates to survivability. We feel that we can do that with only two aircraft in our initial phase.

The statement quoted above suggests that the Army's goal in the AAH program's first phase was the construction of "advanced development" prototypes. From this perspective, the program's two phases would appear to be mildly analogous to the evolution from "validation" to "engineering development," as set down in DoD 5000.1.[20] However, this was not the case. Indeed, project office personnel insist that *both* phases of the AAH program involved engineering development prototypes, because the service felt that it could not truly judge the merits of test vehicles unless they met, or at least came close to meeting, military specifications, detailed design criteria, and so forth. Phase I of the AAH program thus involved full scale engineering development of the airframe; Phase II involved full scale engineering development of the complete system.

As the program began, the service envisioned a five-year effort (see Fig. D.1). Contracts went out to winning firms in June of 1973. Competitive tests were slated to begin in January of 1976, to be followed by source selection in June of that year—precisely three years after contract award. In Phase II the winning contractor would build three more prototypes, testing of which would begin late in 1977. A final production go-ahead was expected in June of 1978. The final production rate was projected to be eight aircraft per month, and the service hoped to buy between 450 and 500 aircraft.

The Managerial Approach

Having imposed a design-to-cost goal on the attack helicopter, OSD sought to ensure that contractors would have the flexibility necessary to trade performance for cost should that be necessary. The Army seems to have preferred more specification detail and somewhat tighter managerial control. The managerial precepts embodied in the AAH RFP were an amalgam of these opposing views.

An attempt was made to give the contractors freedom and flexibility in the development process by substituting "bands" of acceptable performance for point performance targets. Four minimum essential performance goals were defined: speed (145 kn), rate of climb (450 fpm at 4,000 ft and 95°), firepower (8 TOWs, 800 rds of 30-mm ammunition), and endurance (1.9 hr). These four basic performance goals became "floor" parameters. The AAH RFP contained a "J13 clause" that allowed contractors to make design tradeoffs in the area *above* these four "floors" without service approval, and on the basis of the priorities listed. Further, it allowed contractors to suggest changes in the floor parameters so long as doing so promised significant cost savings.

The RFP's short length of 225 pages belied a high degree of detail in the actual specification. Because the Army felt that its AAH concept was well proven and that the subsystem technologies were well in hand, in DSARC I it sought and won approval for an *engineering*

[19] U.S. Senate, Committee on Armed Services, *FY 1974 Authorization for Military Procurement*, Hearings, 93d Cong., 1st Sess., Part 7, p. 4792.

[20] Department of Defense Directive #5000.1, Subject: Major System Acquisition, 30 November 1976, pp. 3-4.

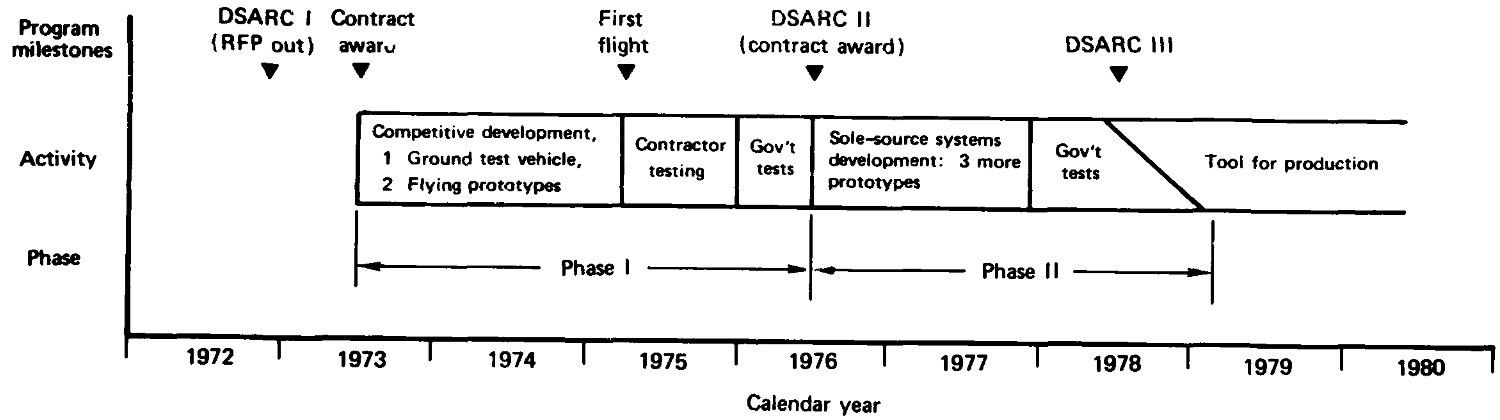


Fig. D.1—Projected AAH development schedule

development of the sort normally undertaken later in the development process, usually after DSARC II. Consequently, the AAH RFP cited hundreds of pages of other technical documents, including all pertinent military specifications. It specified most subsystems, even though many of these were provided by the government, and it detailed the first-phase test and evaluation schedule to include general guidelines for contractor testing.

Similarly, the RFP's four floor performance parameters were sufficiently stringent to place severe limits on contractor flexibility. More important, the existence of a competitor made each contractor wary of pursuing all but the most peripheral design tradeoffs; after all, Army operational and technical experts, not OSD personnel, would judge the flyoff. Thus, even in the absence of tight controls emanating from the project office, the flexibility granted by the J13 clause was more apparent than real.

Finally, although the RFP listed only nine information requirements, the ninth was essentially an "access list" by means of which the service could ask for any *other* information deemed necessary, so long as that information could be made available with minimal additional effort on the contractor's part. However, the RFP also gave the project manager control over all information requests going to contractors. And each project manager has used this power to keep this aspect of the program as austere as possible. Moreover, the existence of stiff competition has generally allowed the service to stand back from the project—at least in the first phase of the program—and let competition control each contractor. In the words of several participants in it and other Army projects, the AAH program remains the most austere and flexible development program the Army has managed in recent years.

THE DEVELOPMENT PROGRAM, PHASE I

The AAH RFP carried the usual 90-day response limit, and by February 15, 1973, the service had received six proposals from five firms. Lockheed submitted two designs somewhat similar to its Cheyenne. Sikorsky and Boeing Vertol proposed designs that stressed commonality with the UTTAS prototypes each firm was then developing for another Army program office. Bell and Hughes Helicopters each submitted one proposal. The Army awarded cost-plus-incentive-fee contracts to Bell and Hughes in June 1973.

Contrasting Managerial Approaches

Bell brought to the design of its AAH candidate, dubbed the YAH-63, years of experience in the medium-helicopter business. The firm had the plant capacity and expertise to do much of its work on the AAH in house and advertised this approach as genuinely advantageous. On the one hand, having major subcomponents designed in house made it quite easy to coordinate design iterations and would, Bell maintained, make continuing modification in the future easier. On the other hand, shorter lines of communication between designers and engineers was thought to save time and money.

By contrast, although Hughes has had considerable experience in building helicopters (it provided thousands of OH-6 light observation helicopters for use in Vietnam), the firm lacked the in-house capability to construct a medium helicopter like the AAH, and chose instead a "team approach" to building its candidate, called the YAH-64. Hughes itself designed the aircraft and assembled the prototypes. For design consultation, as well as the construction of most major subcomponents, however, the firm assembled the following team of 12 contractors:

THE YAH-64 DEVELOPMENT TEAM

1. Bendix Corporation's Electric-Fluid Power Division: Design and fabrication of drive shafts, couplings, and electrical power systems.
2. Bertea Corporation: Hydraulic control systems.
3. Garrett Corporation: Design and fabrication of infrared suppression and integrated pressurized air systems.
4. Hi-Shear Corporation: Manufacture of the canopy and crew escape system.
5. Litton Precision Gear Division: Main transmission and engine nose gear boxes.
6. Menasco Manufacturing, Incorporated: Landing gear units.
7. Solar Division of International Harvester Corporation: Production of APU.
8. Sperry Flight Systems Division: Manufacture of automatic stabilization equipment.
9. Teledyne Ryan Aeronautical Division: Airframe structure fabrication.
10. Teledyne Systems: Fire control computer.
11. Tool Research and Engineering Corporation: Main and tail rotor blades.
12. Western Gear: Intermediate and tail rotor gear boxes.

Coordinating the efforts of this team had demanded special managerial arrangements. Most notably, Hughes assembled high-level executives (presidents and vice-presidents) from each of these firms every three or four months to discuss the project and each firm's role in it.

This approach involved both costs and benefits. On the cost side of the ledger, Hughes could not possibly control its subcontractors as well as it could have controlled in-house labor. The project manager found it difficult, for example, to demand "rush" work from subcontractors—work that would entail weekends and overtime. Indeed, Hughes had to drop a few of its original subcontractors for lack of cooperation. However, Hughes was able to tap the expertise and experience of fairly stable and long-standing design teams within companies better equipped to work on a particular area of the aircraft than Hughes itself.

Contrasting Technical Approaches

Bell and Hughes proposed different solutions to the attack helicopter design problem. In particular, their designs differed in pilot/copilot placement and in location of the gun in relation to gunner's seat. Consequently, in Phase I tests the Army could not only compare performance in a narrow sense, but test some of the basic conceptual differences that cause debate among rotary-wing advocates.

The most often cited differences between the two candidates was their contrasting placement of the pilot and his copilot-gunner. The Cobra's pilot sat behind the gunner, giving the gunner maximum visibility to place his visually sighted ordnance on target. With its AAH candidate, Bell reversed this seating arrangement on grounds that for antitank work on the European battlefield, the gunner would be looking primarily into his sighting instruments (mainly the FLIR system plus the TOW's daylight visionics). Meanwhile, the AAH pilot would need all the visibility he could get to execute nap-of-the-earth flight maneuvers. Placing the pilot in front also enhanced his ability to handle air-to-air engagements with enemy helicopters.

Hughes recognized the demands low altitude flight placed on the aircraft's pilot but felt

that he could best meet these demands by being as close to the aircraft's center of rotation as possible, a location where he would be acutely sensitive to changes in pitch and attitude. Hence, Hughes located the pilot behind the gunner, just two feet from the main rotor shaft. Moreover, the firm located his seat 19 inches above the copilot's seat, providing him with a good deal of visibility in any case.

Another layout difference that provoked some interest was the gun and sighting system placement. Bell located the 30-mm gun in its aircraft's nose, and placed the FLIR and visionics equipment just behind and beneath it. Hughes reversed this order, placing the sighting equipment in a "chin-bubble," while the gun itself extended from a point beneath the gunner. In part, Hughes chose this location on survivability grounds; in a crash landing, the gun, not the aircraft's very expensive ($250,000 per aircraft) and delicate sighting system, would be crushed. In addition, in this position the gun would not black-out the FLIR system each time it fired. But the difference had conceptual ramifications as well; it allowed the service to test the relative effectiveness of guns located well away from (Bell) versus just beneath (Hughes) the gunner.

Bell and Hughes took other fundamentally different approaches to aircraft design. Hughes followed the so-called "McDonnell Douglas approach" of designing the aircraft, then subtracting 10 percent of the structural weight to arrive at a goal and adding strength where necessary. Bell used a much more conservative approach. Indeed, one Bell engineer noted that, structurally, "we're using DC-3 technology,"[21] meaning that the Bell prototype was overdesigned structually.

Each contractor chose a different rotor system. Bell's design used a two-bladed rotor, a choice justified on grounds of survivability. Performance requirements demanded a total additive rotor width (or "chord") of 80 inches. Bell's engineers decided that two blades, each over 40 inches wide, "would permit sufficient spar separation [within each blade] in event of even a 23-mm explosive shell hit so that one spar would survive to carry the necessary rotor loads." Each blade thus contained two widely separated stainless steel spars, with aluminum honeycomb between, boron-composite leading edges, and plastic-covered honeycomb trailing edges.[22]

Designers at Hughes chose to use four rotor blades, with each blade having a shorter chord than those on the Bell prototype. Although the YAH-64's rotor blades are only half as wide as the Bell blades, each has five spars running its length, a feature designed to stop the spread of cracks. To enhance the aircraft's survivability, Hughes used high-strength laminated stainless steel straps for blade retention and a static mast that allows autorotation in the event that the aircraft's dynamic mast fails (a concept proven on the firm's OH-6).[23]

The firms also used different rotor hub design techniques. Bell's design used a "teetering" rotor, while Hughes used a fully articulated system. These designs differ in the way the rotor forces are transmitted to the rotor shaft and the helicopter body. Each firm claimed that its design afforded quicker response to control inputs and better nap-of-the-earth flight capability.

Test and Evaluation

Actual testing of the AAH candidates began in April 1975 for Bell and June 1975 for Hughes with ground tests of each firm's Static Test Article. Because the service ultimately

[21]Bulban, "Bell Stresses AAH In-House Development," p. 36.
[22]Ibid.
[23]J. Philip Geddes, "The Hughes YAH-64 AAH Advanced Attack Helicopter," *Interavia*, September 1975, p. 974.

intended to field a finished attack helicopter, these ground tests came to include more test hours than the service originally envisioned, as first the contractors and then the service itself sought to achieve lifetime qualification of major components on each prototype. Thus, although *flight* testing of the AAH prototypes included only enough hours to compare the two aircraft and come to a source-selection decision, *ground* testing pushed to fully qualify components of each helicopter for military use.

Actual flight testing began within a day of the contract milestone for first flight; Hughes, in fact, first flew its YAH-64 on September 30, 1975, the contract milestone, while Bell had its first YAH-63 aloft on October 1. Thus commenced nine months of contractor testing.

Although the RFP made some comments about the form testing should take, contractors were generally free to design their own test programs. The project office limited the flight envelopes each contractor could explore, reviewed test plans and results, and conducted major test program reviews every four months. The project manager also witnessed major tests as each contractor ran them. Beyond this, contractors could test as they saw fit.

Their tests surfaced a variety of unexpected technical problems in each design. Both candidates experienced lateral stability problems and excessive flight loads on main rotors. The Hughes prototype had an additional problem with "rotor slap." In response to the Army's requirement that AAH candidates be transportable aboard the C-141, Hughes had shortened the rotor mast of its design below lengths dictated by long-standing rules of thumb. In flight maneuvers the rotor came dangerously close to the top of the aircraft's canopy, and this forced Hughes to extend the rotor mast 10 inches. To facilitate air transport, Hughes added a quick removal feature to its rotor system. By February 15, 1976, Hughes had completed this design change.

Finally, and perhaps most important, Hughes found it necessary to reengineer the tail section of its aircraft. The initial design had a low horizontal tail element that doubled as a workstand for maintenance personnel. Company tests showed that in this position the tail was susceptible to downward propwash from the main rotor at speeds as low as 15 to 20 kn. Because this caused problems during landing, Hughes switched to a T-tail. Although the horizontal tail element could no longer serve maintenance purposes, its position high on the vertical stabilizer brought it into the main rotor's propwash at much higher speeds (50 to 60 kn), speeds at which the tail was actually flying and hence less susceptible to rotor interference. The switch also made it possible to compensate for the propwash effect by shifting only the leading edge of the element, rather than turning the entire stabilizer on its axis. Hughes incorporated this design modification before government testing began.[24]

Bell encountered problems with the input drive shaft leading from the engines to the transmission of its prototypes. The firm redesigned this shaft over the course of contractor testing. As a result of other technical problems, one of the Bell prototypes crashed in May 1976, just before government competitive tests were to begin. The crash eliminated that prototype, and, rather than enter the flyoff with only one aircraft, Bell converted its static test article to a flying prototype for government tests.

Both firms had problems meeting the May 31, 1976 deadline for delivery to the service for competitive testing. The Bell prototype's crash caused a four-week delay in the delivery of the firm's #1 prototype and a seven-week delay in delivering the #2 model. And though Hughes delivered its prototypes by May 31, it had yet to complete fatigue life testing of major components. Hence, three weeks passed before a safety-of-flight release could be obtained and the prototypes could be flown.

---

[24]Donald E. Fink, "Few YAH-64 Design Changes Expected," *Aviation Week & Space Technology*, January 10, 1977, p. 83.

The prototypes each firm finally delivered to Edwards AFB differed only slightly. Each firm had been asked to instrument one prototype for stability and control tests and the other for fatigue and structural tests. Hughes also varied minor design features—such as vertical scale instrumentation—between its two prototypes to demonstrate alternatives to service evaluators.

Despite a late start, the AAH flyoff ran quite smoothly and ended on schedule, for several reasons. First, the Army trained government pilots in the aircraft before their delivery to Edwards AFB. Second, before testing began, the AAH program manager obtained agreement among the Army's test agencies as to precisely what data each agency wanted. This minimized coordination problems; pilots could fly a basic series of tests, from which each test agency would extract the appropriate data. Third, the contractors handled all maintenance and had skilled personnel in sufficient numbers to keep availability rates high. Finally, the flyoff was blessed with good weather from start to finish. Government Competitive Testing thus ended on September 30, 1976, as had been planned.

In side-by-side missions flown by Army crews dedicated to fly only one firm's prototype, each attack helicopter logged 102 hours, bringing total test hours for each helicopter design to 450. Development and operational tests were totally integrated, with a 50-50 split between these two test modes. Four OTEA (user) pilots and six engineers were used.

The most important thing about the flyoff is that it clearly determined source selection. Numerous program personnel agree that Bell would have won a "paper competition" based on the original AAH design proposals. The firm's design looked better, and Bell came into the competition with a fine reputation and a degree of experience in the field. That Hughes won the flyoff testifies both to the superiority of the Hughes design and to the amount of learning both that firm and the service had accrued over the course of the development and testing program.

The service learned, first, that the Hughes prototype outperformed the Bell design by a considerable margin. Indeed, the conceptual differences that separated the two designs were nearly all resolved in Hughes's favor. The four-bladed rotor proved both quiet and effective, but the Bell rotor created enough drag to prevent that design from meeting the RFP's speed requirements; and Hughes's fully articulated rotor hub proved more responsive than Bell's teetering rotor. Locating the pilot near the aircraft's center of rotation proved beneficial as well, as did locating the 30-mm gun just beneath the gunner. Although Bell had trouble meeting the RFP's speed requirement, the Hughes aircraft not only met all requirements but climbed faster than the service required.[25] On December 10, 1976, the Army awarded Hughes the contract for Phase II AAH development.

Hughes's Phase II development proposal contained a variety of minor changes in its YAH-64 design that reflect learning accrued from contractor and government tests. These changes were subsequently incorporated into the firm's Phase II prototypes. One change was to sweep the rotor tips. Although the Hughes prototypes surpassed the Army's minimum speed requirements, both had difficulty reaching the Army's Phase II high-speed goal of 204 kn. In the words of Thomas R. Stuelpnagel, Vice President and General Manager of Hughes Helicopter, "As we approached the high-speed range, the build-up in rotor vibrations told us we ought to pay some attention to the blade tips."[26]

Windshield panes in the aircraft's canopy were reshaped. The Army's RFP asked for a

[25]Fink, "Few YAH-64 Design Changes Expected," p. 83.
[26]Ibid., p. 82.

flat-pane windshield to cut down on glare. Flight tests showed that flat plastic panels vibrated too much, and Hughes changed to slightly curved panels in the sides and top of the canopy.

Over the course of Phase I, Hughes built and tested an exhaust gas cooling system (necessary to suppress infrared signature), which it called the "black hole" exhaust duct. Based on a Hughes-developed material called "Low Q," this system

> absorbs heat from the engine exhaust flow and radiates it slowly into the air flow around the nacelle. Exhaust flow through each duct is used to draw ambient air into the dynamic section of the helicopter, cooling the transmission—via oil heat exchangers—and the engines.[27]

Aside from eliminating exhaust plume signature problems, the system also saved 60 pounds of weight and let the engine achieve 50 more shp than was possible with the exhaust gas cooling system Hughes originally installed on its AAH candidate.

The pounds saved and power generated by adding the "black hole" helped Hughes resolve a problem with the total weight of its helicopter. Whatever weight savings the firm thought it had achieved early in the design cycle[28] had disappeared by the time government tests began; by then, the weight of the YAH-64 had risen to 1000 pounds more than expected. Hughes managed to pare 600 of this 1000 pounds in its Phase II proposal through design changes in the original prototype. Weight savings and power increases afforded by the "black hole" exhaust duct made further savings unnecessary: The final version "will have the same performance at a mission weight of 13,600 pounds as Hughes originally proposed at the 13,200-pound mission weight."[29]

The Hughes Phase II design proposal also included an even longer rotor mast than the lengthened mast incorporated during Phase I testing. Hughes decided to add another six inches to the mast to improve rotor blade clearance. The rotor retained the quick-remove capability, making it possible to meet the Army's transportability requirement.

These were minor changes, and service representatives asserted before the Senate in 1977 that the AAH test program had not "encountered any major technical problems."[30] Moreover, prototype tests clearly allowed the service to select the better vehicle. In this sense, the AAH flyoff achieved the goals of high performance at low cost set for the Phase I development at its start.

COST AND SCHEDULING PROBLEMS IN THE COMPETITIVE PROTOTYPE PHASE

As was noted in the discussion of the UTTAS program (Appendix C), the Army's helicopter prototypes were funded with cost-plus contracts. The contractors expected, and received, reimbursement for cost overruns that occurred during the competitive prototype phase. Thus, unlike the Air Force prototype programs with their fixed-price arrangements, the AAH experienced cost overruns and schedule slippage from the very beginning. This section exam-

---

[27]Fink, "Few YAH-64 Design Changes Expected," p. 82.

[28]As development began, the Hughes model was supposed to be a full ton lighter than the Bell design. See Geddes, "The Hughes YAH-64," p. 972. An article written over a year later noted that the Hughes model had acquired excess weight as development progressed. See Fink, "Few YAH-64 Design Changes Expected," pp. 82-83.

[29]See Fink, "Few YAH-64 Design Changes Expected." Note that these weight increases are separate from those associated with changes in the AAH requirement made toward the end of Phase I development and hence discussed below. See Geddes, "Hughes Helicopters," p. 729.

[30]U.S. Senate, Committee on Armed Services, *FY 1978 Authorizations for Military Procurement*, Hearings, 95th Cong., 1st Sess., Part 8, p. 4116.

ines cost and schedule problems during the development of the two prototype designs. *Like the previous case studies, the discussion will be in terms of FY 81 dollars unless otherwise noted.*

Work on the AAH candidate designs formally began in June 1973 with Phase I CPIF contracts awarded in the amounts shown in Table D.2.[31] By July 1974 both contractors began to experience unanticipated cost increases, due less to technical problems (those lay down the road) than to inflation. The Army had based its original cost calculations on an expected inflation rate of 4 percent, but that figure soon proved unrealistic. As a result, Bell and Hughes found themselves paying considerably more than they had planned for parts, labor, and materials. Unable to obtain additional funds to pay for those cost increases as they arose, the Army chose to defer some work that had been programmed for FY 1975 until the next year. A six-month slippage in the original Phase I schedule was negotiated and, according to the announcement in February of 1975, it added almost 30 percent to the cost of the prototype phase.[32] Bell and Hughes both elected to invest company funds to keep their projects moving as fast as possible, knowing that they would receive reimbursement under the terms of the CPIF contract.

Table D.2

AAH Prototype Contract Target Prices

	Contract value ($ millions)		
Contractor	FY 72 $	Then-Year $	FY 81 $
Bell	43.2	44.7	84.7
Hughes	67.8	70.2	132.9
Total	111.0	114.9	217.6

Once testing began, the technical problems discussed in the previous subsection began to take their toll in cost increases. In addition, Hughes experienced a decrease in other contract work, forcing the Army to absorb more of that firm's overhead. And a legal ruling moved the costs of Bell's Phase II proposal work from the firm's overhead to its AAH budget, again raising AAH program costs. In February 1976 the Army requested a $14.6 million reprogramming of funds. With congressional approval, the Army provided Bell $5.5 million and Hughes $9.1 million. (These costs are in then-year dollars.) As a result of those cost increases, both firms lost their incentive fees.

However far ahead of schedule Bell may have been in June 1975, neither firm delivered its prototypes ahead of the rescheduled target date for government testing. Bell's prototypes arrived at the flyoff site four to seven weeks late, and the Hughes aircraft arrived on time but

[31]See "AAH Awards Keyed to Production Costs," *Aviation Week & Space Technology*, July 2, 1973, p. 17. The article gives no reason for the disparity in contract values. Program office personnel suggest, however, that the Hughes bid was higher in part because the firm was to carry the development of its chain gun, but Bell's design used a gun developed and paid for under other contracts.

[32]See "Costs to Force Stretch in AAH, UTTAS," *Aviation Week & Space Technology*, September 2, 1974, p. 22. See also "AAH," *DMS Market Report*, May 1976, p. 2.

with insufficient ground-test data. Hence, Phase I development took the full (rescheduled) amount—42 months (including the flyoff) rather than 36.

The cost growth and schedule slippage incurred during prototype development is summarized in Table D.3. That phase of the AAH development took six months longer and cost almost 40 percent more (in constant dollars) than predicted. Nonetheless, the total program cost distribution shown in Table D.4 makes it clear that the competitive prototype phase did not add significantly to program cost. Since the candidate helicopters were developed in Mil-Spec detail and the prototype effort nearly completed airframe development, it might be appropriate to consider only the duplicated effort—i.e., half the cost of the prototype phase—as an additional expense. This amounts to 4 percent of the total program cost in constant dollars, or less than 2 percent in then-year dollars.

Table D.3

COST CHANGES INCURRED DURING PROTOTYPE DEVELOPMENT
($ millions)

Program Change	Cost Growth FY 72 $	FY 81 $	Then-Year $
Baseline cost target (12/72)	111.0	217.6	114.9
Cost growth			
6-month Phase I slip (2/75)	31.9	62.5	53.6
FY 1976 reprogramming (2/76)	10.8	21.2	14.6
Total	153.7	301.4	183.1

SOURCE: AAH Program Office.

Table D.4

AAH/AH-64 TOTAL PROGRAM COSTS, INCLUDING PROTOTYPES
($ millions)

	Base-Year $ (FY 72)		Present-Year $[a] (FY 81)		Then-Year $ (FY 73-78)	
Item	$	%	$	%	$	%
Prototype (Phase I)	153.7	7.4	301.4	7.2	183.1	3.1
AH-64 FSD (Ph II)	529.3	25.3	1037.8	24.8	923.0	15.8
Procurement	1407.8	67.3	2838.3	67.9	4750.2	81.1
Total	2090.8	100.0	4177.5	100.0	5856.3	100.0

SOURCE: Prototype cost: Table D.3; FSD and Procurement: AH-64 SAR, June 1980.

[a]Totals may not sum because of rounding.

The Transition to Phase II

The Army originally envisioned Phase II of the AAH development program as a two-and-one-half year, sole-source FSD effort designed to add the TOW system and several other subsystems to the winning airframe candidate from Phase I. In Phase II the winning contractor was expected to modify his two Phase I flying prototypes and build three more, bringing all five helicopters to fully equipped production configuration. The work was expected to involve few risks: TOW had already been mounted on a helicopter when the AAH program began, and contractors were expected to design their airframes to readily accept the TOW system. There seemed little reason to doubt that, following a second set of operational and development tests, the service would be able to make a production decision in January 1979.

By the time the program's first phase had ended, these original expectations had changed radically. Estimated development costs had doubled in then-year dollars, and even in real terms they had risen 75 percent. The development schedule, including the competitive prototype phase, had slipped by two years.

These changes in development cost and schedule were only marginally related to actual development work on the flight vehicle itself. Rather, they derived primarily from changes in AAH requirements, congressionally directed changes in the program's original funding schedule, a pre-DSARC reappraisal of the program's overall cost and schedule, and changes in the program's test schedule made possible by successful testing at the end of Phase I.

Congress and the Elimination of Lead Time Items. The first of these changes actually was made as Phase I development work proceeded, although it did not affect Phase I cost and schedule. In 1975 the Congress refused to fund the purchase of Prototype Development Lead Time Items for the program's second phase on grounds that one set of PDLTI would be wasted once a winning contractor had been selected. The service argued without success that most of these funds would be used to establish a position in the supplier's queue and could be canceled for the losing competitor. Most of the PDLTI actually purchased for the losing design could be salvaged for use on other Army projects. The elimination of these funds delayed construction of the three additional YAH-64s needed in Phase II by five months, until the long lead time items could be acquired. The net cost of carrying the winning contractor over this delay came to the equivalent of $25.1 million in FY 81 dollars.

Shifting Requirements. By far the most important changes in the program's estimated cost and schedule resulted from a series of requirements changes imposed on the program over the year preceding the end of Phase I. In February 1976 the ASARC opted to replace the TOW system with the newer Hellfire antitank missile. This made it necessary to replace the TOW's visual sighting system with a more technically complex and capable sighting system called the Target Acquisition Designation System/Pilot's Night Vision System (TADS/PNVS). In September 1976 and at OSD's direction the service also substituted for the U.S. 30-mm ammunition used in the aircraft's 30-mm gun a cartridge used by several of the nation's NATO allies. These changes substantially altered the AAH program.

The Hellfire Decision. The Army began the development of a successor to the TOW system in 1972, about the same time it began work on the AAH. In that year the Army's Missile Command awarded contracts to Hughes Aircraft and Rockwell International for the competitive advanced development of an antitank missile that would track laser beams reflected from its target. The service also planned to make the missile modular in construction to permit later development of infrared sensing seekers for the device.

Those seekers promised to give the service a much sought-after "fire-and-forget" antitank missile, meaning one that did not have to be tracked by its firer as it traveled to its

target. Lack of such a capability remains one of the TOW's chief inadequacies; having fired a TOW missile, an attack helicopter (or any other launch vehicle) must remain in sight of its target, hence vulnerable, throughout the missile's flight, which may last over ten seconds. Laser illumination for the Hellfire could be provided by an attack helicopter, an infantryman, or a scout helicopter equipped with an illuminator; and except in cases where the attack helicopter itself illuminated the target, it could fire its missile and move on to a concealed position or another target. From this capability the system derived its name: HELicopter-borne FIRE-and-forget missile.

The Hellfire was designed to provide a variety of other advantages over TOW. TOW can be fired to a range of 3750 meters at best. This puts TOW-equipped helicopters within range of the Soviet ZSU-23/4, a quad 23-mm antiaircraft gun with a range of about 4000 meters. By contrast, the Hellfire's range (in excess of 4000 meters) would allow the attack helicopter to stand off and fire from a less vulnerable position on the battlefield.[33] And the Hellfire's larger warhead should penetrate greater thicknesses of armor than the TOW warhead, thus providing the service with a hedge against advances in Soviet armor.

Few doubted when both the AAH and the Hellfire programs began that the Hellfire would eventually find its way onto the AAH at some point; the AAH program began, however, with the goal of initially adding TOW during Phase II, and incorporating the Hellfire system at "a later date during the helicopter's 15-year anticipated life."[34] To be sure, in March 1972 Major General William J. Maddox, the Army's Chief of Aviation, evinced a certain ambivalence on the subject:

> The relationship between Hellfire and the aerial TOW will be dependent upon the current effectiveness studies being completed which concern systems characteristics and costs; the existing enemy threat; and the existing status of the aerial TOW system. Therefore, a definitive answer cannot be made at this point in time.[35]

Still, AAH development went forward on the assumption that TOW would be integrated into the winning airframe candidate during the program's second phase.

By 1975, however, both Rockwell and Hughes had successfully completed advanced development work on the missile, and the Hellfire and AAH developments seemed to be running in parallel tracks. In tests conducted that year Hellfire showed high accuracy: of 14 missile fires, 13 hit their targets, one narrowly missed. In 1976 the service selected Rockwell International to continue into the missile's engineering development phase. With the missile's development proceeding apace and the AAH program's first phase coming to a conclusion, the ASARC announced in February 1976 its decision to include Hellfire in Phase II of the AAH program. In April 1976 the DSARC endorsed the Army's decision. Because contractor tests had just begun on the AAH prototypes and the flyoff was only a few months off, the service decided not to rewrite the original AAH RFP. Instead, it sent each contractor a letter of intent indicating that proposals for Phase II development work should be based on Hellfire rather than TOW.

The decision had an immediate effect on the AAH program's cost and schedule. Although funding for the missile's continued development remained separate from AAH funding, inte-

---

[33]See U.S. Senate, Committee on Armed Services, *DoD Authorization for Appropriations for FY 1979*, Hearings, 95th Cong., 2d Sess., Part 6, p. 4830, which includes a full listing of what the service perceives to be the Hellfire's advantages over present systems.

[34]"Army Helicopter Details Coming," *Aviation Week & Space Technology*, October, 23, 1972, p. 16.

[35]U.S. Congress, House Committee on Appropriations, Subcommittee on the DoD, *2d Supplemental Appropriation Bill, 1973*, Hearings, 93d Cong., 1st Sess., Part 3, p. 83.

grating the missile into an airframe that until 1976 had been designed to accept the TOW system was expected to add five months to the AAH development schedule, and $84.3 million was added to the helicopter's overall development cost estimate.[36]

Finally, the decision had a marginal effect on the original AAH requirement. Hellfire added about 400 pounds to the flyaway weight of the fully armed AAH. To compensate, the service decreased the number of 30-mm gun rounds the helicopter was required to carry, from the 800 listed in its original AAH requirement to 500.

TADS and PNVS. Given its range advantage over TOW, the Hellfire missile cannot be used optimally with the TOW's optical sights. Thus, the month after it announced the inclusion of Hellfire in the AAH program's second phase, the service announced another change in the original AAH requirement—the addition of a special sight, TADS/PNVS, which offered a much wider range of capabilities than the TOW's visual sighting system, as the project manager's description suggested:

> TADS is the device that enables the long-range day/night/marginal weather detection/recognition/designation and the attack of hostile targets. To do this, the system incorporates direct view optics, television, and forward-looking infrared sensors, indirect sensors coupled with a laser rangefinder, and a precision designator, a laser spot tracker, and the system stabilization that allows long-range precision attack of point targets.
>
> The pilot's night vision system is a FLIR [Forward-Looking Infrared] in a stabilized turret coupled to the pilot's integrated helmet and display sight system we call HADSS, which enables nap-of-the-earth flight at night and in marginal weather. Together, the capabilities of the TADS and PNVS give the Army for the first time an airborne attack capability around the clock and in adverse weather.[37]

The service set out to develop TADS in the mid-1970s as part of its Advanced Scout Helicopter project. At the time, the service apparently hoped to have the winning AAH contractor develop another TADS; the Army could then choose the better TADS design for incorporation into both the AAH and ASH.

The ASH program, however, entered a period of extended limbo soon after it started. With the decision to add Hellfire to the AAH, the service altered its original plans and initiated a competitive prototype development program for both TADS and a pilot's night vision system. The system RFP went out in September 1976, by which time the service had decided to integrate a visual optics system similar to the TOW's sight into the overall TADS/PNVS package. Cost-reimbursable contracts for the overall system were awarded to Martin-Marietta and Northrop on March 10, 1977, with the first critical design review scheduled for October 1977, delivery date for the first prototyped TADS/PNVS set for August 1978, and source selection slated for December 1979. The system's development became a subprogram of the AAH project, run by a project manager within the AAH PMO and funded by the AAH budget.

Although development of some of the TADS/PNVS components began at about the same time that development work began on the Hellfire missile, the sighting system was not as well developed by 1976 as the missile itself. The technical challenge of developing TADS/PNVS was not so much in its diverse capabilities as in its packaging. For the most part, individual systems existed that could perform one or more of the functions TADS/PNVS will

[36]U.S. Senate, Committee on Armed Services, *FY 1977 Authorization for Military Procurement*, Hearings, 94th Cong., 2d Sess., Part 9, p. 4698.

[37]Quoted in U.S. Senate, Committee on Armed Services, *FY 1978 Authorization for Military Procurement*, Hearings, 95th Cong., 1st Sess., Part 6, p. 4049.

perform. The problem was in putting these systems into a light weight (470-lb) package that would fit inside the chin turret of the AAH. Once there, the system must also function reliably in the presence of the high vibration levels common to helicopters. Meeting that challenge was the main task facing Northrop and Martin-Marietta as they competitively developed their system prototypes.

Largely for this reason the decision to add TADS/PNVS to the AAH requirement was accompanied by an announcement that four months had been added to the aircraft's development schedule. Because the AAH program was to carry the cost of developing the sighting system, the service also added the equivalent of $215.3 million (in FY 81 dollars) to the overall AAH development cost estimate. And in September 1976, $8.8 million more was added to account for the addition of direct-view optics to the TADS/PNVS package.

The ADEN/DEFA 30-mm Ammunition. In March 1976, OSD directed the Army to replace the Weapons Command (WECOM) 30-mm cartridge originally planned for the AAH with a cartridge used in the ADEN and DEFA 30-mm guns used by several of NATO's European members. The U.S. Marine Corps was also using the cartridge in its Harrier aircraft. The goal of that change was to increase the prospects for interoperability among the various 30-mm guns in use with the Atlantic Alliance.

Initially, the service was not enthusiastic about the change. At the time the directive was passed on to the Army, the Europeans had in use some five different kinds of ADEN/DEFA ammunition, none of which was "standard"; adopting an ADEN/DEFA round did not guarantee interoperability. Furthermore, the round's ballistics and shape differed from those of the WECOM 30-mm round, and its inclusion in the AAH would make changes necessary in the Hughes chain gun, which the service intended to use on the winning AAH prototype. Finally, because the changes promised to increase the gun's weight and the ADEN/DEFA round itself weighed more than the WECOM round, use of the European round promised to increase overall weight of the 30-mm system, forcing compensatory changes in other AAH requirements.

Despite its expressed concern for the effect of the change, the service agreed to incorporate the new round and sought to alleviate its concerns through negotiations with its NATO allies. Meetings of representatives from France, the United States, the United Kingdom, and the Federal Republic of Germany produced agreement among the first three on common use of a single ADEN/DEFA *derivative* that the U.S. Army agreed to develop. The new round would offer improved fuzing and a dual-purpose warhead, thereby making it more effective than the WECOM round it replaced. The United States agreed to bear the costs of this new round's development (about $9 million). In September 1976 the U.S. Army (rather than the Marine Corps) was given control of that development, and the service formally notified its AAH contractors of the change.

Although the development of the ammunition is not funded in the AAH program, the shift to ADEN/DEFA ammunition made necessary minor adjustments in the original AAH requirement. Like the Hellfire decision, the ADEN/DEFA decision increased the weight of the load the aircraft had to carry. Thus, just as it had lowered the aircraft's required ammunition-carrying capacity from 800 to 500 30-mm rounds when it added Hellfire to the AAH, the service lowered this requirement still further—to 320 rounds—when it added the ADEN/DEFA requirement.[38]

Although these requirements changes were not expected to take the aircraft's unit flya-

[38] "Status of the Advanced Attack Helicopter Program," GAO Report, February 25, 1977, p. 11.

way cost over the $1.7 million DTC goal,[39] they had a major effect on program development cost and schedule. Among them, these changes added a total of nine months to the Phase II estimated development schedule and increased the estimated development costs by 46 percent. Moreover, they changed the program's very nature. Originally, development of the AAH airframe, although deemed a "low risk" enterprise, had been the most uncertain portion of the AAH program. After 1976 major uncertainty had been transferred to the aircraft's subsystems, especially TADS/PNVS, which presented higher risk than had the airframe itself. The General Accounting Office noted the altered nature of the program in a report[40] published soon after Phase II began:

> The AAH program has undergone numerous changes, mostly in the last year. Program cost, schedule, and technical characteristics have been revised considerably. Because of these changes, the AAH program is now dependent upon concurrent successful development of the Hellfire missile, TADS and PNVS, and new 30-millimeter ammunition.

Use of the phrase "concurrent successful development" highlighted the fact that the shift in requirements tied the development of a low-risk but expensive system—the AAH—to the development of less expensive but higher-risk subsystems. Because program delays in the high-risk development would incur the costs of delays in the AAH program as a whole, the GAO recommended that "the Congress and the Secretary of Defense closely examine the status of the Hellfire missile and other supporting subsystems when evaluating the AAH program."

Approaching DSARC II. Over the fall of 1976 the service conducted a full review of the AAH program's cost and schedule in preparation for the December 1976 DSARC II. The baseline cost estimate was updated, adding $45.9 million to the overall development cost estimates. Also, to allow Hughes Helicopter sufficient time to correct deficiencies in its prototype that surfaced during Phase I test and evaluation, the Army added five months to the Phase II schedule, and this in turn added $76.9 million to program costs.

At the DSARC meeting itself, $24.3 million was recouped from the AAH program cost estimate on the grounds that the selection of Hughes made certain tests redundant. According to the chief cost analyst with the program, no single factor accounts for this reduction. Rather, it resulted from a series of changes in the program's overall cost estimate which reflect, among other things, the specifics of the Hughes Phase II proposal. Table D.5 summarizes the development cost changes that have been discussed up to this point.

As shown in Table D.6, the approved total DE for developing the AAH was established at $935.7 million in then-year dollars, or $609.4 in base-year dollars. Translated into FY 81 dollars, the development cost becomes $1194.9 million. Of this latter figure, Phase II was expected to cost $893.5 million.

Table D.6 presents a summary of the cost growth that has taken place in the AAH program since DSARC II, using the same format as that used for the summaries of the three other prototype programs reviewed in this study. The cost values are shown in base-year, then-year, and FY 81 dollars and separate tabulations are given for the development and procurement phases. The sum of the baseline DE, shown on the top line of each group, plus the cost changes (variance) that have surfaced since DSARC II equal the Current Estimate on

---

[39]As the program manager noted in his testimony in FY 1979 before the Senate Committee on Armed Services, "Our design to unit production cost flyaway, all systems aboard, is $1.7 million (in FY 72 $)." *DoD Authorization for Appropriations for FY 1979*, Hearings, 95th Cong., 2d Sess., Part 6, p. 4817.

[40]"Status of the Advanced Attack Helicopter Program," GAO Report, February 25, 1977, p. 6.

Table D.5

DEVELOPMENT COST AND SCHEDULE CHANGES DURING PHASE I
($ millions)

Program Change	Date Announced	Schedule (months)	Cost Growth FY 72 $	Cost Growth FY 81 $	Cost Growth Then-Year
Baseline estimate	1974	67	345.1	676.7	467.4
Changes					
Prototype cost growth	(See Table D.3)	6	42.7	83.7	68.2
Deletion of long lead time items	6/75	5	12.8	25.1	24.6
Change in escalation index		--	--	--	20.0
Hellfire addition	2/76	5	43.0	84.3	67.2
TADS/PNVS	3/76	4	109.8	215.3	187.8
Direct view optics	9/76	--	4.5	8.8	7.7
ADEN/DEFA	9/76	--	1.3	2.5	2.1
Baseline cost update	9/76	--	23.4	45.9	39.3
5-month Phase II extension	10/76	5	39.2	76.9	71.1
DSARC deliberations	12/76	--	-12.4	-24.3	-19.7
New estimate		92	609.4	1194.9	935.7

SOURCE: AAH Program Office.

Table D.6

AH-64 Program Acquisition Cost
($ millions)

Item	Base-Yr (FY 70) $ Cost	Base-Yr (FY 70) $ % of DE	FY 81 $ Cost	FY 81 $ % of DE	Then-Year $ Cost	Then-Year $ % of DE
Development (Quantities: DE = 9, CE = 9)						
Development estimate	609.4	100.0	1194.9	100.0	935.7	100.0
Variance:						
Quantity	.0	.0	.0	.0	.0	.0
Schedule	42.1	6.9	82.5	6.9	73.9	7.9
Engineering	16.6	2.7	32.5	2.7	32.5	3.5
Estimating	-2.5	-.4	-4.9	-.4	.0	.0
Other	.0	.0	.0	.0	.0	.0
Support	17.4	2.9	34.1	2.9	32.4	3.5
Economic					31.6	3.4
Total variance	73.6	12.1	144.3	12.1	170.4	18.2
Current estimate	683.0	112.1	1339.2	112.1	1106.1	118.2
Procurement (Quantities: DE= 536, CE= 536)						
Development estimate	1266.3	100.0	2553.0	100.0	2822.4	100.0
Variance:						
Quantity	.0	.0	.0	.0	.0	.0
Schedule	69.2	5.5	139.5	5.5	387.8	13.7
Engineering	.0	.0	.0	.0	.0	.0
Estimating	32.4	2.6	65.3	2.6	343.5	12.2
Other	.0	.0	.0	.0	.0	.0
Support	39.9	3.2	80.4	3.2	95.2	3.4
Economic					1101.3	39.0
Total variance	141.5	11.2	285.3	11.2	1927.8	68.3
Current estimate	1407.8	111.2	2838.3	111.2	4750.2	168.3
Total program (Quantities: DE= 545, CE= 545)						
Development estimate	1875.7	100.0	3747.9	100.0	3758.1	100.0
Variance:						
Quantity	.0	.0	.0	.0	.0	.0
Schedule	111.3	5.9	222.1	5.9	461.7	12.3
Engineering	16.6	.9	32.5	.9	32.5	.9
Estimating	29.9	1.6	60.4	1.6	343.5	9.1
Other	.0	.0	.0	.0	.0	.0
Support	57.3	3.1	114.6	3.1	127.6	3.4
Economic					1132.9	30.1
Total variance	215.1	11.5	429.6	11.5	2098.2	55.8
Current estimate	2090.8	111.5	4177.5	111.5	5856.3	155.8

SOURCE: September 1980 SAR.

the bottom line, as projected in September of 1980. The following sections trace the AAH cost growth and schedule slippage that had surfaced by September 1980.

Phase II: YAH-64 Full Scale Development

No sooner had DSARC II been completed than the program's funding and schedule were drastically changed. Harold Brown took office as Secretary of Defense in January 1977, and almost immediately cut in half the Army's FY 1978 AAH budget request of $200 million. Brown's rationale had to do with the aircraft's survivability:

> It is not clear that the helicopter is the most effective platform to carry out the antitank and armored vehicle mission. Doctrinal limitations on AAH tactics to insure survivability raised the question of its advantages over fixed-wing close-support aircraft. In view of this, it is appropriate to reconsider the objectives of the AAH program.[41]

The Secretary's budget cut forced the service once again to reschedule its Phase II program. As the AAH program manager noted before the Congress early in 1978,

> Hughes Helicopters was restricted on fiscal year 1977 expenditures to smooth the hiring rate and to control Hughes' subcontractor obligations. Deferment of funding was primarily accomplished by delaying design and fabrication of the three phase-2 prototype aircraft. A 60-month phase-2 program was developed and negotiated.[42]

This represented a ten-month slip in the program's Phase II schedule. The cost of this additional time was estimated to be $114.7 million.

In its FY 1978 Appropriations Act the Congress restored two thirds of the Defense Secretary's $100 million reduction, arguing that the Defense Department had failed to show a "valid basis" for the reduction. Because the service had already negotiated a 60-month Phase II program with Hughes, however, it was not able to reschedule the program in precise proportion to the amount of the funding increase. Rather, it managed to pare four months and $60.6 million from the rescheduled program. An additional result of this funding change was a slippage of three months in the TADS/PNVS development schedule, made necessary to ensure that the TADS/PNVS prototypes could be tested sufficiently under the new 56-month AAH development schedule.

Because of the slippage in the development program, however, procurement has been pushed further into the future, driving up *then-year* procurement cost estimates in response to expectations of greater amounts of inflation in the out years as well as changes in the OSD inflation indexes for those years. Procurement cost estimates have also changed marginally in response to changes in what is included in the procurement cost category.

The actual development program of the AAH is shown in comparison with the original development schedule in Fig. D.2. For Hughes, Phase II work was essentially that set down for the winning contractor when the program began in 1972, although, of course, the work was stretched over the program's elongated schedule. Between January and November 1977 the firm continued to correct the design problems that surfaced during Phase I test and

---

[41]This is a summation of the Defense Secretary's position as it was presented to the Congress by the Army's Assistant Secretary for R&D. See U.S. Senate, Committee on Armed Services, Subcommittee on Tactical Air, *FY 1978 Authorization for Military Procurement*, Hearings, 95th Cong., 1st Sess., Part 6, p. 4051.

[42]Quoted in U.S. Senate Committee on Armed Services, Subcommittee on Tactical Air, *FY 1979 Authorizations for Appropriations*, Hearings, 95th Cong., 2d Sess., Part 6, p. 4821.

evaluation, and a full scale mockup review held in November 1977 assured the program manager that this had been accomplished.

During this period, additional support requirements and a revised baseline cost estimate raised support costs by $20.6 million. Meanwhile, construction of the three additional prototypes called for in its Phase II contract was delayed until the long lead time items were delivered in FY 78. In March 1980, three months behind schedule, the TADS flyoff was completed, and on April 9th Martin Marietta was declared the winner. Hughes then integrated the fire control systems into the airframe.

Cost increases resulted from redesign of the tail section ($32.5 million), additional logistic support for operational testing ($13.5 million), and three months of "sustaining program effort" ($28.4 million). A minor overestimate of $4.9 million served as a partial offset to these increases so that the total Phase II cost increases (as of September 1980) totaled $144.3 million in FY 81 dollars.

AH-64 Procurement

At the time of DSARC II, a baseline cost estimate for the procurement of 536 AH-64 helicopters was established, equivalent in FY 81 dollars to $2553 million. By late 1980, changes approved during Phase II had added $285.3 million to the procurement estimate and the schedule had slipped by a year. The stretchout was caused by the delay in funding long lead time items and an extension of the FSD phase. This accounted for $139.5 million, nearly one-half of the estimated procurement cost growth shown in the September 1980 SAR.

An even larger increase, $164.7 million, was incurred in the Support variance area for new support equipment for alternative missions plus associated data and installation charges. However, more than half of this cost growth was offset by an $84.3 million reduction in initial spares requirements. To the extent that these spares will have to be bought later to build up inventory stocks, this is merely a postponement of the funding problem.

Finally, $65.3 million was charged against the Estimating category to bring the current AH-64 estimate into line with a recent cost review. The UTTAS stretchout had an indirect effect on AH-64 costs because of engine commonality—the AH-64 engine buy was advanced to a higher position on the cost learning curve as more of the UTTAS engines moved to later-year deliveries.

Cost Growth Summary

The Development total CE for the AAH program stood at $1339.2 million in September of 1980, a level 12 percent above the baseline DE. This result is quite favorable compared with the experience of contemporary military acquisition programs. It is only fair to point out, however, that the DE was revised after the airframe had completed its competitive prototype development. That (Phase I) development effort had witnessed a period of inflation-induced schedule slippage and a number of unexpected changes in the AAH's armament and fire control system. If the baseline estimate that preceded Phase I had not been revised upward at the time of DSARC II to reflect these changes, development cost growth would have been calculated as almost double the original estimate. In the AAH case, at least, preceding DSARC II by a competitive prototype phase improved the baseline estimate.

Procurement cost growth, as noted in Table D.6, stood at 11.5 percent for the AAH in September of 1980. This is a fairly good showing, but of course AAH acquisition has a long

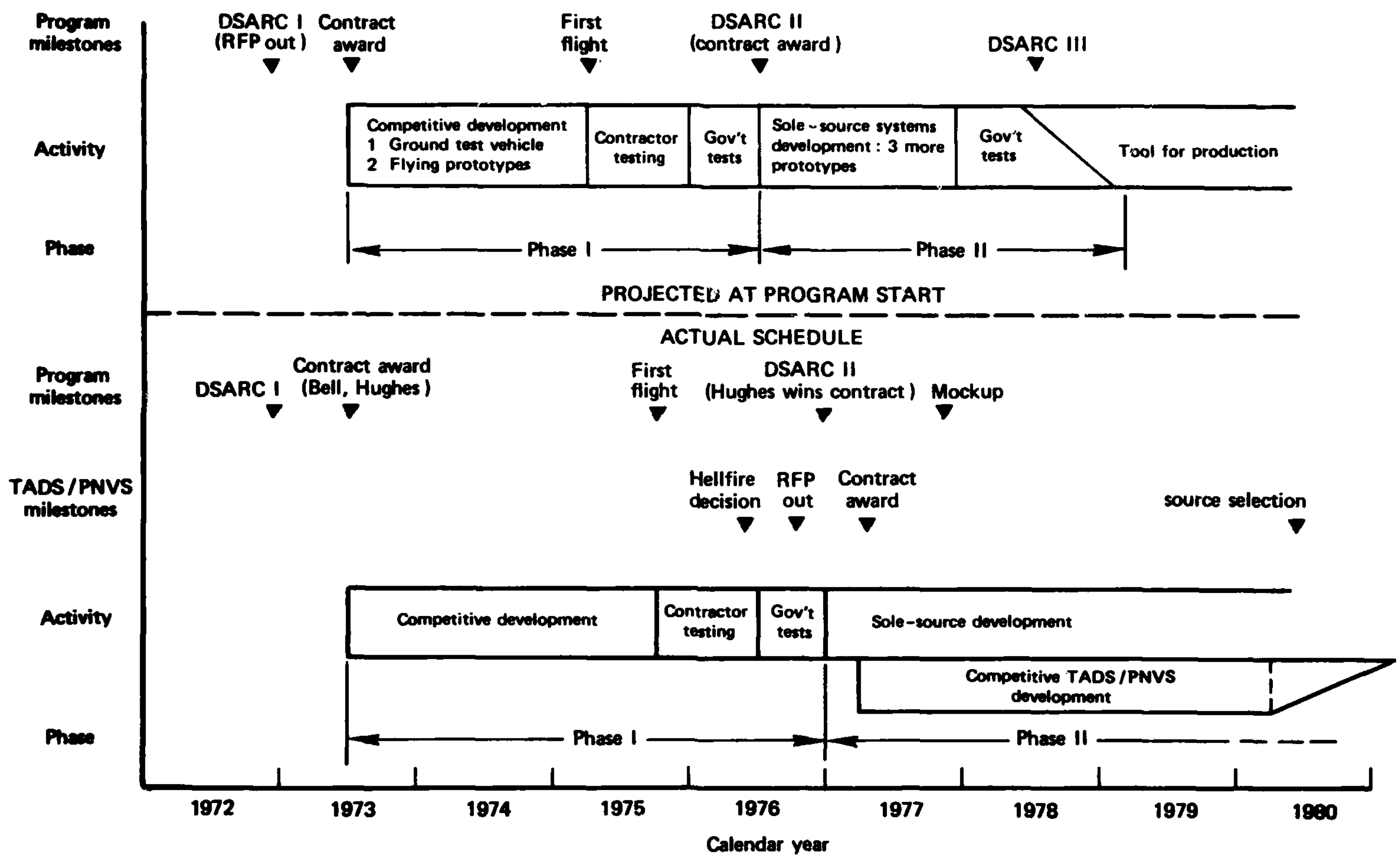


Fig. D.2—Projected and actual AAH development schedule

time yet to run. Total program costs also were calculated as 11.5 percent above the baseline DE.

It is too early to judge whether the existence of prototype hardware will contribute to a more accurate estimate of AAH procurement costs. The development phase, however, is nearly complete. Therefore, we can compare the predicted cost growth for that phase with the growth that occurred in acquisition programs that lacked such prototypes upon which to base their estimates.

First, it is necessary to deduct the cost of the AAH competitive prototype phase shown in Table D.4 ($301.4 million). That phase was completed before DSARC II and its costs were known. Therefore, it was not a part of the development cost prediction. This adjustment reveals that the accuracy of the estimate for AH-64 full scale development still is much better than average—16 percent below the eventual costs. However, the full scale development of the AH-64 consisted only of making some required modifications to the airframe and integrating the armament systems; the airframe design was practically complete at the end of the prototype phase. This qualification is added to make it clear that the AAH development cost growth percentage is not strictly comparable to those of other programs, and conclusions based on the AAH experience should be tempered by that fact.

Design-to-Cost Goal (Base Year FY 72 $)

The DTC goal for the AAH program has increased over the years as the OSD definition evolved to encompass more and more cost elements that presumably contribute to aircraft average flyaway cost. Beginning with a goal of $1.6 million (in FY 72 base-year dollars) for 536 aircraft produced at a rate of eight per month, $104 thousand was added to cover nonrecurring (startup) costs. Then a management reserve of $100 thousand was specified, and system/project management ($49 thousand) and mods/engineering changes ($28 thousand) followed. The DTC goal had reached $1.881 million at that point. Finally, OSD factored in the cost of "imposing cost accounting standards" and it allowed for design changes—Hellfire, TADS, PNVS, etc. (AH-64 SAR, June 1980, p. 9). Thus the approved goal (as of September 1980) was $2.091 million (in FY 72 dollars), and the SAR gave the current estimate for the helicopter as $2.099 million.

Flyaway costs are not separated from the support elements in the procurement group of the cost breakdown in Section E of the AAH SAR. However, average procurement cost per AAH (including support equipment and spares) is $2.63 million. Thus, a flyaway cost of $2.099 million implies that the cost of support requirements is 25 percent of flyaway costs—a reasonable assumption. This tends to support the statement that AAH flyaway costs do not exceed the DTC goal in its latest revised form.

OBSERVATIONS

This analysis concerns the contribution of the competitive prototype phase to the total AAH program. On this point a fundamental judgment is that prototyping in the first phase greatly reduced the development uncertainties associated with the airframe's design, performance, and cost characteristics. Contractor testing surfaced technical problems in each firm's prototype design that were solved on the spot or were dealt with in fairly specific terms in each firm's FSD proposal. Government testing answered the Army's questions about the

aircraft's ability to meet required performance characteristics. And the existence of a prototype phase before DSARC II helped make the baseline cost estimates more realistic, which contradicts the experience of the other prototype examples in our study. The reason for this positive result on the cost estimates for the AAH is easy to identify: All of the large engineering (scope) changes and associated schedule slippage—up to this point at least—that greatly affected the AAH cost and schedule estimates occurred during the prototype phase. In the other prototype programs, the large cost changes followed the DSARC II approval to proceed into full scale development. In the AAH case, many of the cost-sensitive issues had been settled before the program go-ahead was sought.

Competitive prototyping in the program's first phase seems to have afforded two additional benefits: Program office personnel argue that it helped control cost growth, and they feel that competition allowed them to step back from direct control of the two AAH contractors, allowing the firms themselves to make critical design decisions without direct service oversight or interference. The value of these benefits is difficult to quantify. However, the fact that these arguments are being made by individuals whose experience extends to other, noncompetitive projects suggests that they are worthy of careful consideration in any listing of pros and cons for competitive prototyping.

Finally and perhaps most important, competitive prototyping in the program's first phase apparently led the service to select a different contractor than it would have chosen on the basis of the proposals originally submitted in response to the AAH RFP. This is no small point. The expense of a competitive prototyping effort is small in the context of the total program cost of a large acquisition program. If it reveals information that improves the quality of a major decision, then it performs a vital function in the system acquisition process.